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FLOATING OIL RECOVERY DEVICE

New Mexico State University

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FLOATING OIL RECOVERY DEVICE

by

Physical Science Laboratory
New Mexico State University
Las Cruces, New Mexico 88001

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this document may be better
studied on microfiche.

for the

ENVIRONMENTAL PROTECTION AGENCY

WATER QUALITY OFFICE

Program No. 15080 FWO
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February, 1971

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ABSTRACT

Flow bench tests of a model rotating belt-Couette flow oil recovery device were conducted in a calm water environment primarily, although a few tests were conducted in the presence of waves. These tests revealed clearly that the device is capable of harvesting oils over a broad range of viscosities at the rates and purities specified by the EPA, if the inlet can be made to "track" the water surface.

Analyses were conducted to design a catamaran vessel suitable for mounting the Oil Pickup Unit (OPU) and also providing the requisite surface following performance. Vessel response analyses showed that the required surface following behavior cannot be provided by the catamaran itself, but can be achieved by floating the OPU and decoupling this assembly from the vessel in heave and surge. A servo control for the foil device used at the OPU inlet will further enhance the surface tracking behavior.

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TABLE OF CONTENTS

Section		Page No.
I	Conclusions	1
II	Recommendations	3
III	Introduction	5
IV	OPU Model Tests	7
V	OPU System Design	13
VI	Hull Design Analysis and Layout	15
VII	Vessel Response Characteristics	17
VIII	Acknowledgment	19
IX	Symbols	21
X	Appendix A (Figures 1-42)	23
XI	Appendix B (Dr. Breslin's Report)	64

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FIGURES

		Page No.
1	OPU Test Model	23
2	OPU Test Model	24
3	OPU Test Model Belt	25
4	OPU Test Model With Boom	26
5	OPU Test Channel	27
6	Test Channel Wave Paddle	28
7	OPU Test Model Carriage	29
8	OPU Test Model and Symbols	30
9	Oil Test Sample Box	31
10	OPU Test Model Carriage & Sample Box Frame	32
11	Oil Thickness Measurement	33
12	Test Data Form	34
13	Oil Test Samples	35
14	Oil Recovery Rate	36
15	Oil Recovery Rate	37
16	Oil Recovery Rate	38
17	Oil Recovery Rate	39
18	Oil Recovery Rate	40
19	Dimensionless Oil Recovery Rate Parameter	41
20	Dimensionless Oil Recovery Rate Parameter	42
21	Dimensionless Oil Recovery Rate Parameter	43
22	Dimensionless Oil Recovery Rate Parameter	44
23	Oil Recovery Efficiency	45
24	Oil Recovery Efficiency	46

FIGURES

		Page No.
25	Oil Recovery Efficiency	47
26	Oil Recovery Efficiency	48
27	OPU Test Model (top view)	49
28	Oil Recovery Performance	50
29	Oil Recovery Performance	51
30	Oil Recovery Performance	52
31	Oil Recovery Performance	53
32	Oil Recovery Performance for Various Test Configurations and In Waves	54
33	Wave In Test Channel	55
34	OPU Prototype Configuration	56
35	Hull Lines – Configuration A	57
36	Hull Body Plan – Configuration B	58
37	Horsepower Required – Catamaran	59
38	Catamaran Oil Recovery Vessel	60
39	Catamaran Bridge and Hull Structure	61
40	Catamaran Bridge Structural Beam	62
41	Catamaran Heave & Pitch Amplitude Response	63
42	Catamaran Heave & Pitch Phase Response	64
43	Wave Lengths for Various Encounter Frequencies at Selected Speeds	74

SECTION I
CONCLUSIONS

The following conclusions are appropriate upon completion of Phase I of this program.

Model Tests

The OPU model tests have demonstrated that the proposed technique will achieve the required harvesting rates in calm water. It has further been demonstrated that the water content in the harvested oil can be constrained within the specified limit of 10 percent. The percentage of oil left on the water appears to be at or near the specified limit of 1 percent, although uncertainties in the measurements preclude a clear conclusion. The performance is largely insensitive to the broad range of viscosities of the oils employed in the tests, except as noted in Test Results Summary on page 7. The test results obtained were under conditions of full scale for the significant parameters involved, such as oil film thickness, vessel speed, belt speed, and belt-plate gap. The only scaling was of the belt width, the roller diameter, and the distance travelled along the plate. The latter parameter is conceded to have a small deteriorating effect in a full scale system, since the friction losses will be greater.

It is quite evident that the model tests in waves produced inferior test results. This was expected, however, since the model was constrained on the carriage so that it could not follow the wave surface. In the PSL letter of 26 March 1970 containing final Proposal Revisions, the following was stated: "It should be pointed out that the OPU test bench model will not respond to wave action in the way that the catamaran-mounted unit would because the model is restrained against all degrees of motion. This constitutes the major limitation to rough-water testing with the flow bench, but an initial indication can be obtained as to the prospects of good rough-water performance."

The testing with waves served to emphasize the importance of achieving excellent surface following performance with the OPU.

The testing with the boom was conducted primarily as an attempt to sweep the entire channel of oil, so that after a test run a sample of the swept water behind the model could be checked for oil content. This approach was unsuccessful because the particular boom configurations employed were not of proper design. Since PSL was directed to avoid any effort in the area of boom design, it was deemed advisable to abandon this test technique in favor of another method. The point here is that the unfavorable test results obtained with booms should not be interpreted to mean the OPU is incompatible with booming techniques.

Although the construction features of the model prevented setting gaps larger than 0.87", the data suggests that even greater recovery rates can be achieved with larger gaps, assuming the oil film thickness at the entrance can be brought to about the same dimension. The data further suggests that the peak oil recovery efficiencies will be reached at gaps greater than 0.87", except for kerosene.

Catamaran

Analyses were conducted to design a catamaran vessel suitable for mounting the Oil Pickup Unit (OPU) and also providing the requisite surface following performance. Vessel response analyses showed that the required surface following behavior cannot be provided by the catamaran itself, but can be achieved by floating the OPU and decoupling this assembly from the vessel in heave and surge. A servo control for the foil device used at the OPU inlet will further enhance the surface-tracking behavior.

SECTION II

RECOMMENDATIONS

The following recommendations are offered for the consideration of the Water Quality Office in regard to this program.

The program should be continued to accomplish the scale model testing of the vessel and OPU as an assembly in a scaled rough-water environment, in a manner which will create no unrealistic motion constraints as was the case with flow bench testing. Two options have been considered as to the means of accomplishing these tests.

Utilize a private or government-owned model basin facility, employing either a 1/8 or 1/4 scale model of the vessel and OPU. Conduct tests in the presence of regular and irregular waves, the latter being representative of the spectrum encountered on the open sea. Conduct tests in two series, the first with water only and the OPU belt not operating, for adjustments and verification of required surface following characteristics. The second series would involve operations with an oil film on the water, the OPU operating, and some type of simple boom arrangement. This approach offers the advantage of precise control of vessel speed and wave enrironment plus the availability of force measurements for more accurate characterization of the vessel response than was possible during the analyses reported herein. The disadvantages are high cost and the inability to simulate quartering waves to assess roll response.

Conduct 1/4 scale model tests of the catamaran and OPU in a trench tank as originally proposed by PSL, with and without oil as described in Option 1, and with regular and irregular waves. Follow these tests with open-water trials (no oil) on Lake Caballo, approximately 75 miles north of the University campus. The advantage of this approach is lower cost and the possibility of a more realistic wave environment during the lake tests, especially quartering waves. The disadvantages are less precision in the control of test parameters such as vessel speed and wave amplitude and frequency, and no force measurement capability.

The Physical Science Laboratory recommends that Option 1 be followed if government-owned model basin test time can be secured at little or no cost to the EPA. Otherwise PSL recommends adoption of Option 2.

Complete the detail design of the OPU with particular attention to the decoupling linkages and the foil servo control. This should be accomplished first so these features can be incorporated into the scale model.

In addition to the decoupling linkage and the foil servo control, incorporate instrumentation into the model which will permit assessment of the surface following characteristics, such as a resistance probe which senses the position of the oil-water interface with respect to the upper surface of the foil.

Provide a scaled working recovery belt and oil removal provision, plus the necessary gear for harvested oil sample collection aboard the model. This is in accordance with PSL's original proposal.

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SECTION III

INTRODUCTION

It is the intent of the EPA (Environmental Protection Agency) -WQO (Water Quality Office) to develop a floating oil recovery system with performance superior to existing devices and techniques for removing spilled oils from both protected and unprotected waters. Some major requirements of the system, as outlined by the EPA are as follows.

Harvest capacities for light to heavy oils of at least 3000 gal./hr of oil with 10% or less water content while operating in protected waters with up to 2 foot waves in combination with 20 mph winds and 6 knot currents.

Harvest capacities for light to heavy oils of 50,000 gal./hr of oil with 10% or less water content while operating in unprotected waters with up to 5 foot seas in combination with 20 mph winds and 2 knot currents.

Vessel with oil harvesting equipment must be capable (while not recovering oil) of speeds of at least 12 knots under the sea conditions listed above.

System must be reliable, economical to operate and maintain, and readily transportable to the affected area and quickly put into operation.

An oil recovery system which will accomplish these objectives has been proposed to the EPA by the Physical Science Laboratory of New Mexico State University. The basic part of the proposed system utilizes a rotating drumbelt device operating on Couette flow theory in combination with a catamaran vessel. Additional components required in the open sea are two (2) ocean going tug boats and flexible floating booms, between the tugs and the catamaran, for thickening the oil.

Several tasks related to the proposed system were assigned to PSL under contract with the EPA. They include conducting a performance analysis on the OPU, designing, building, and testing a working model of the OPU and performing hull design analysis and layout work. This document describes the work accomplished under this contract.

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SECTION IV

OPU MODEL TESTS

Description of Test Components and Procedure

Model

The primary parts of the model are the belt, drive and idler rollers, belt tension adjustment roller, lower plate, upper plate, hydrofoil, wiper blade, drive motor, drive belt, pulleys, and plexiglas sides, see figures 1 and 2 (drive components not shown). The rollers, hydrofoil, and upper and lower plates are all made from Ponderosa pine and coated with white epoxy finish. The belt, see figure 3, a product of Arthur S. Brown Manufacturing Co. of Tilton, New Hampshire, is a 4 ply 5/64 in. thick endless woven belt treated topside with 5-56B teflon white and treated pulley side with HT-50 black. The width of the belt is 4 in. and the circumference is 12-25/32 in. When the belts were received from the Brown Co. they appeared to be unsatisfactory because the outer surface was both water and oil permeable. This condition was corrected by turning the belt inside out and applying five (5) coats of teflon spray. The inside was already impermeable to both oil and water due to the HT-50 black treatment. After spraying with teflon it also became both hydrophobic and oleophilic, the desired characteristics. The wiper blade for removing oil from the belt surface is a strip of neoprene mounted in an aluminum block. The belt-plate gap is varied by loosening the wing nuts and moving the plate up or down. The maximum gap obtainable is 0.87 in. The plate mounting holes in the plexiglas are oversize to allow for this adjustment. The upper plate and hydrofoil can also be moved up or down (or fore or aft) accommodated by oversize mounting holes.

The belt drive motor is a 3/8 in. drill motor mounted on a hinge on the forward slope of the plexiglas sides. The hinge provides a means for adjusting the drive belt tension. The drive motor speed is varied by utilizing an adjustable autotransformer mounted on the carriage frame.

On several test runs a boom was attached to the model for thickening the oil ahead of the inlet, see figure 4. In checking out the operation of the model, prior to the recorded test series, a simple boom model with a throat section 6 in. long and a straight sided vee section 17 in. long was tried. It was unsatisfactory due to severe turbulence in the throat area which caused a drastic reduction in oil recovery rate. The present boom with its long gently curved sides is a considerable improvement over the earlier one although still not entirely satisfactory as explained on page 6, Other Configurations and Wave Tests.

Test Channel

The test channel is 96 ft long having inside dimensions of 10 x 22-1/4in. See figure 5. Plexiglas panels between the supports allow viewing of the water and oil surfaces. A plywood panel with a crank was installed near one end for making waves. See figure 6. A motor driven continuous cable moves the carriage with the OPU model on steel angle tracks the full length of the channel. The cable drive motor is a reversible gear head type rated 12 to 24 volts dc, torque rated 75 ft-lbs @ 24 volts dc. The power supply for the drive motor has a variable dc voltage output and is rated at 1000 amps.

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Test Fluids

The fluids used in the tests are shown in the following table:

NAME	NO.	VISCOSITY @ 60° F lb-sec/ft^2	SPECIFIC GRAVITY
Enco Gear Oil	GX90	1.94×10^{-2}	0.8607
Enco Lube Motor Oil	SAE30	4.81×10^{-3}	0.8877
Enco Lube Motor Oil	SAE10W	2.36×10^{-3}	0.8708
Kerosene		4.50×10^{-5}	0.8184

All products were purchased from the Humble Oil and Refining Co. The viscosities and specific gravities were converted from SUS and API units supplied by the oil company for temperatures of 100° and 210° Fahrenheit.

Instrumentation

The primary instrumentation consisted of cameras, manometers, a tachometer for measuring belt speeds, a timer for use in computing model speeds, and oil sample box and timer circuitry, see figure 7. A 16 mm movie camera was used to record flow characteristics at the belt inlet and gap area. (In water only). A 35 mm still camera was used to record manometer and tachometer readings. Four (4) pressure orifices were located in the plate as shown in figure 8. The forward orifices were directly under the axis of the forward roller and the rear orifices were under the axis of the aft roller. The differential pressure across the side orifices is sensed by the forward mounted "U" tube and the differential pressure across the center orifices is sensed by the aft mounted "U" tube. The tachometer cable is connected to the idler roller and the instrument dial indicates linear belt speeds in feet/second.

The oil sample box, see figure 9, is towed behind the model in a low slung frame with wheels which roll on the steel angle tracks. See figure 10. It is made of plexiglas and has a spring hinged door in front for admitting oil from the model during the test run. The sample box and timer circuitry includes the following items: solenoid, two (2) single pole double throw switches, and two (2) switch trippers. The solenoid is a pull type with 1 inch stroke and 7-½ lbs pull and is activated by 110 ac voltage to open the sample box door at the proper time. The two switches are mounted side by side on the carriage directly above the channel edge with their actuating arms down for contact with the switch trippers. The switch trippers are thin strips of spring steel mounted vertically eight (8) feet apart on top of the channel wall. The following describes the operation of the sample box and timer circuitry: With the carriage at rest several feet from the 8-foot sampling section the power is applied to the belt drive motor first and then to the carriage drive motor. The carriage is accelerated to a constant speed prior to reaching the first switch tripper. When one of the two switch arms contacts the first tripper, power is applied to the timer and solenoid starting the timer and opening the sample box door to admit the oil sample. At the completion of the 8-foot run the other switch arm contacts the second tripper and the circuit is again opened stopping the timer and deenergizing the solenoid, allowing the sample box door to be closed by its spring type hinge. Before and after the 8-foot travel period oil from the model is ejected onto the top of the sample box and back into the test channel. After the test run the carriage motor is reversed and as the carriage passes back over the switch trippers the switches are reset in preparation for the next run.

The oil thickness in the sampling section was measured with a scale scribed in 1/100ths of an inch. The scale was held vertically against one of the plexiglas side panels adjacent to the oil layer and the reading taken with the aid of a magnifying glass, see figure 11. Measurements were made at three (3) locations along the test section prior to each run and the average recorded. Because of meniscus effects the error in the readings is estimated to be as much as ± 2%.

Test Procedure

Testing began with several runs in water alone to check out the test bench and model operation. A 16 mm movie camera was used on these runs to record flow characteristics. A total of 241 test runs with oil on the water surface were made varying the primary parameters of fluid type, belt and model speeds, and gap dimension. Also several runs were made with each of the following changes: with boom, without hydrofoil, hydrofoil chord plane parallel to oil-water interface plane except submerged 1/8" in water, tilt angle 65°, and with waves. The majority of the runs were made in calm water, without the boom, with the hydrofoil chord plane in the oil-water interface, and with a tilt angle of 74.2°. All data were recorded on forms similar to the one shown in figure 12, and later transferred to the form shown. Symbol definitions appear on page 14.

At the conclusion of each run the fluid in the sample box was poured into a graduated cylinder, see figure 13. The fluid remained in the cylinder for 1-½ to 2-½ hours before water content was measured. It was found that this time period was sufficient for virtually all water to separate from the oil. For kerosene, however, the settling period required was much less. In order to conserve the volume of oil required for testing, a 50 foot section of the channel was blocked off from the channel ends by means of wood gates. The gates effectively contained the oil, but not water. When adding oil to this section the weight of the oil would force water through the gates into the ends of the channel, thus lowering slightly the water level in the test section. When removing oil from this section the converse was true. As a result of the small variation in water level occasional adjustments in model height were necessary. Incidently, when changing oils the OPU was used most effectively in removing the oil for which the tests had been completed.

Discussion of Test Results

Oil Recovery Rate

The oil recovery rates are represented in figures 14 through 17 as a function of belt-speed to model-speed ratio and belt-plate gap. The oil recovery rate value of 0.87 gal./sec indicated by a dashed line in these figures is equivalent to a full scale recovery rate of 50,000 gal./hr (5-½ ft wide belt) neglecting Froude number scaling effects. While the data shows considerable scatter it is readily apparent for all of the oils tested that the wider the gap the greater the oil flow rate for the range of gaps considered. The oil recovery rate for the widest gap (0.87") is shown in figure 18 for all of the oils. These data show quite clearly that the flow rates are inversely proportional to the belt-speed to model speed ratios. It would appear that the more closely the belt speed is matched to the model speed the more effective the recovery of oil, at least as long as the oil layer thickness ahead of the OPU inlet is not greater than the belt-plate gap.

A dimensionless oil recovery rate parameter was computed and plotted as a function of belt-speed to model-speed ratio in figures 19 through 22. These plots show that the oil recovery rate is essentially independent of the oil type for those oils tested.

Oil Recovery Efficiency

Oil recovery efficiency (the percent oil removed) is determined by comparing the amount of oil removed from the water surface with the amount of oil available for removal. The volume available is computed by knowing the model inlet width (4-½ inches), the oil thickness, and the distance traveled during sampling (8 feet).

The percent of oil removed from the water surface is shown in figures 23 through 26. From these figures it would appear that belt-plate gap has little if any effect on the percent of oil recovered for gear oil GX 90 and motor oil SAE 30, but not so for motor oil SAE 10 and kerosene. A gap of 0.87 inches produces the highest efficiency for SAE 10 and a gap of 0.75 inches results in the highest efficiency for kerosene. Also indicated in the plots for the higher viscosity oils is a reduction in efficiency at the lower belt-speed to model-speed ratios. This is the opposite effect to that indicated for oil recovery rate where the flow increases with decreasing speed ratios. It is noted that several data points indicate efficiencies greater than 100 percent. It is believed that there are two sources for these apparent discrepancies. One, the estimated ± 2% error in oil thickness measurements, and two, additional oil drawn into the model from the sides of the inlet due to sink action as depicted in figure 27.

It was observed in several test runs that oil piled up at the belt inlet indicating that the belt speed was too low for that particular model speed, gap, and oil type. In these cases recovery efficiencies were generally low because the model was not able to remove all of the oil available for recovery, consequently, the excess oil flowed out and around the leading edges of the model sides (the opposite effect to the sink action). When, of course, the speeds and other variables were correct for removing all of the oil available there was usually room for a little more to enter the model due to the fact that the oil thickness was always several hundreths of an inch less than the gap dimension, thus resulting in efficiency values exceeding 100 percent.

Oil Recovery Performance

A summary of the results of the oil recovery rate, the percent oil recovered, and in addition, the percent water in the recovered fluid appears in figures 28 through 31 plotted as a function of belt-plate gap. These curves were constructed by using the computed averages for all data points for each gap dimension. These data show the widest belt-plate gaps of 0.75 and 0.87 inches to be most favorable to all three qualities of performance for all oils tested. For SAE 30 and GX 90 oils the value of the percent water in the oil peaks at a gap setting of 0.62 inches. The reason for this was that the model was set too low (hydrofoil chord plane was below the oil-water interface) for the nine (9) runs on SAE 30 and the following three (3) runs on GX 90. How much too low is unknown, however, for subsequent tests the model was raised so that the hydrofoil chord plane was at the oil-water interface resulting in a significant decrease in water content. The very low water content for SAE 30 at a 0.75 inch gap resulted from a small adjustment required in the model height. Due to the small variation in water level mentioned on page 4, Test Procedure, the model height had to be adjusted occasionally. Because the model height was not adjusted after each run or even as often as every 4 or 5 runs, the hydrofoil chord plane was not always exactly at the oil-water interface plane. This was reflected in small changes in both the percent water content in the oil and the percent of oil removed.

The rise in water content for SAE 30 between gaps of 0.75 inches and 0.87 inches is due to slight oil pile-up at the belt inlet on several runs.

Other Configurations and Wave Tests

The three (3) primary quantities; oil recovery rate, percent of oil removed, and the percent of water in the oil are compared in the form of a bar chart, figure 32, when changes in the model configuration were made and waves induced. Again, the values are averages of several test runs. The standard configuration, also included on the chart, is that for which the test results have just been discussed. Test runs were made only with SAE 30 and kerosene. The chart shows that adding the boom to the model, decreasing the tilt angle to 65°, or inducing waves, significantly reduces the oil recovery rates. With the hydrofoil off of the model oil recovery rates are somewhat reduced. During the tests with the boom on, a mound of oil was observed in the throat region just ahead of the belt inlet indicating turbulence which likely forced oil underneath the boom. This mound of oil was also noticed to occur with the earlier boom though larger in size. Decreasing the tilt angle, i.e., increasing the angle between the plate and the horizontal, increased the gravity effects which reduced recovery rate. Also, it is assumed that by decreasing the angle between the hydrofoil chord plane and the plate, oil would have a greater tendency to flow down between the hydrofoil and the plate, reducing the recovery rate. The adverse effect of waves on the oil recovery rate is obvious when considering that the OPU model is fixed vertically relative to the undisturbed water surface. The waves generally had a height of about 2 inches, a speed of 4 ft/sec, and a length of between 42 and 48 inches.

The oil recovery efficiency (not measured with boom on) was quite high, 95% or greater for all tests except for those where the model tilt angle was 65° and in waves. In waves the recovery efficiency reduction was much greater for kerosene than for motor oil SAE 30, a result of the lower wave dampening effect of kerosene. Otherwise the explanations pertaining to recovery rates apply.

The percent of water in the recovered oil was increased significantly by removing the hydrofoil, lowering the model so that the hydrofoil chord plane was 1/8 in. below the oil-water interface, and inducing waves. With the hydrofoil on the model, some water passes down through the gap between the hydrofoil trailing edge and the plate leading edge. With the hydrofoil removed this gap no longer exists and the water which otherwise would pass down and under the model is picked up by the belt, thus increasing the water content in the oil.

It was noted throughout rough water testing that motor oil SAE 30 had a significant effect in dampening the waves. The dampening action of kerosene was very low.

Note: Cursory examination of the test data and attempts to correlate flow rate measurements with analytical computations had indicated a need for modification of the analytical equations, but further effort will be required which was not completed in time to include in this Report.

Test Results Summary

The following statements apply only to the ranges of variables considered in the tests.

Oil recovery rate for all oils increases with gap dimension.

The recovery rates are inversely proportional to belt speed to model speed ratios.

The recovery rates are essentially independent of oil type.

The oil recovery efficiency is affected little if any by the belt-plate gap dimension for gear oil GX 90 and motor oil SAE 30 (high viscosity).

The oil recovery efficiency for motor oil SAE 10 and kerosene (low viscosity) increases with the belt-plate gap dimension, the former rising to a maximum at 0.87 in. gap and the latter peaking at 0.75 in. gap.

The oil recovery efficiency for gear oil GX 90 and motor oil SAE 30 falls off at the lower belt speed to model speed ratios.

Belt speed, model speed, and gap dimension must be of appropriate magnitudes for the type oil to be recovered if pile-up of oil at the belt inlet is to be eliminated and recovery efficiencies are to remain high.

Adding the boom to the model, decreasing the tilt angle to 65°, or inducing waves, significantly reduces the oil recovery rates.

Removing the hydrofoil from the model somewhat reduces the oil recovery rate.

The water content in the recovered oil was considerably increased by removing the hydrofoil, lowering the model so that the hydrofoil chord plane was 1/8 in. below the oil-water interface, and inducing waves.

SECTION V
OPU SYSTEM DESIGN

The Oil Pick-Up Unit (OPU) has not been subjected to detail design in view of the dependence on the flow bench test results.

Several definitive statements can be made concerning general design features. The results of the hull response analysis described in detail in Vessel Response Characteristics, page 11, definitely indicate that it will be essential that the OPU be decoupled from the catamaran hull in heave and surge, in order to provide the required capability to "track" the water surface. The Appendix provides an analysis of the response characteristics of the OPU when decoupled from the catamaran. Although hampered by a lack of knowledge of the applicable wave exciting force coefficients which are required for detailed assessment of the response over the frequency range of interest, the analysis of natural frequencies points out the importance of minimizing OPU weight. The analysis also suggests the sizing and proportions of the OPU flotation "pontoons". From figure 34, the overall shape of the OPU can be observed to consist of the two flotation "pontoons" spaced at the full width permissible (66") between the catamaran hulls, with the oil-plate supported by the pontoons, at an inclination angle of 15 degrees to the calm water surface. Note that the OPU itself does not have an integral oil receiving tank as originally proposed, in order to reduce weight. The two end rollers for the belt are planned to be 24 in. dia. max. fabricated of thin-wall fiberglass tubing with aluminum bulkheads at each end and a stiffener ring in the middle. The aft, driven roller will incorporate a hydraulic drive motor mounted inside. A woven cotton belt treated with teflon, similar to that used in the flow bench tests, will be utilized. The intermediate belt roller used on the flow bench model proved to be unnecessary, and is not included in the prototype design. The oil plate will incorporate integral side plates to contain the oil flow, and also will constitute the bearing supports for the rollers and a gap adjustment mechanism. The side plates will also provide the structural tie-in points for the OPU suspension linkage. An oil collection hopper will be mounted rigidly to the oil plate surface and side plates at the aft end of the OPU. A spring-loaded belt wiper will be mounted to the upper edge of the hopper, with the springs permitting sufficient wiper pressure, plus displacement required for gap adjustment. Two flexible hoses will serve to transfer the oil from the hopper to the hull tanks.

The total OPU suspended weight is targeted at 300 lb max., and this must be achieved by the use of lightweight fiberglass and aluminum materials and possibly composites, for example the OPU plate will be fabricated of a foam-filled aluminum honeycomb core with a fiberglass skin.

The OPU unitized structure, attached to the catamaran at the decoupling linkage, is quite compatible with the concept of breakdown for air transportation. The major elements of the decoupling linkage, i.e. the surge guide rails and constant-tension surge cables, plus the heave guides and heave shock absorbers, will be attached to the catamaran hulls. The OPU incorporates the heave slide and shock absorber end attachment provisions. The heave motion guide rails will incorporate provisions for raising and locking the OPU in an elevated, stowed position during high-speed operation in traveling to and from the spill area.

The model employed in the flow bench tests utilized a foil just ahead of the plate entrance as a flow splitter. This foil was effective in separating the flow at the oil-water interface, causing the water flow to deflect down and the oil to deflect upward onto the plate. The efficacy of this device was indicated by the lower water content in the harvested oil when the foil was employed. The foil does not significantly affect total harvesting rates, nor the percentage of oil removed from the water. The employment of the foil in the full-scale prototype is desirable in the interest of overall harvest efficiency. Referring again to the Appendix, the prognosis that the OPU can be made to follow the water surface to within 12% of the wave amplitude, or within approximately ± 3.5 in. in 5 ft waves, means that to assure that oil does not flow under the OPU it would be necessary to set the ramp inlet at a depth which would assure harvesting a substantial percentage of water. This can be avoided by using the foil with a servo control to further compensate for the residual heave motion of the OPU. As shown in the inset of figure 34, this can be accomplished by a straight forward linear actuator servo which extends or retracts the foil relative to the plate surface. The sensing of the proper foil depth can be accomplished by several means, of which a reflected light measurement is one. Here the significant differences in optical transmissibility and reflectance properties between oil and water can serve to sense the location of the water interface in the heave direction.

It should be noted that the Appendix recommendations (b) and (c) refer to oil recovery techniques which are fundamentally different from the recovery belt-Couette flow system tested on the flow bench. Both represent independent ideas of Dr. Breslin, the author of the Appendix and the program marine engineering consultant. Recommendation (b) involves a scheme whereby a planing plate is installed between the catamaran hulls near the bow, inclined leading edge-up with the vessel operated at high speeds, 10 knots or more. This approach relies on the proper plate trim angle setting which will produce a flow stagnation stream line coincident with the water-oil interface. The oil would be turned forward and up into a vacuum nozzle which would draw the oil flow into hull tanks. The water flow would be deflected down and aft past the plate trailing edge.

In the judgement of PSL this approach suffers from several liabilities, one of which is the loss of the assistance from booms to thicken the oil, since booming at 10 knots or more is a doubtful proposition. Thus the system would be required to operate on extremely thin oil films which would preclude achieving the specified recovery rates. Maintaining the proper plate trim angle in rough water is viewed as another serious problem.

Recommendation (c) suggests a technique similar to the PSL approach except for elimination of the belt system. Here the dynamic head produced by the vessel motion would be relied upon to produce oil flow up the plate, where the flow could be augmented by a vacuum system. This does not appear feasible since early test runs with the PSL system made with the belt not operating clearly showed the head to be insufficient to produce flow up the plate to the output end. A gross calculation shows that the dynamic head developed at a vessel speed of 3 knots is approximately 25 lb/ft^2. A speed of at least 10 knots would be required to make this approach practical, and here again the inability to use booms at this speed mitigates against such an approach.

SECTION VI

HULL DESIGN ANALYSIS AND LAYOUT

This phase of the program has been accomplished largely by Dr. Breslin, except for preliminary vessel equipment arrangement and weight estimates for these items.

The first step in this effort was the selection of the hull configuration. Two sets of hull lines were developed and submitted. Configuration A, shown in figure 35, and Configuration B, shown in figure 36. Both designs are similar, with the same inboard profile, the same length (40 ft), draft (2.5 ft), beam (5 ft per hull), and keel-to-deck height (6 ft). Both utilize parallel, flat inner sides, except that Configuration A does employ shaping of the inner walls at the bow, stern and bottom areas. The pure flat side of Configuration B suggests that it will be more economical to build. The use of "wall sides" in each configuration was dictated by the early expectation that decoupling of the OPU would be necessary, the "wall" sides being necessary to accommodate the relative motions between the OPU and the vessel. Figure 36 shows an early concept for the OPU decoupling guide rails.

The sizing of the hulls was determined by early gross estimates of the "all-up" vessel weight. The weight estimates included allowances for short-term oil storage within the hulls. The vessel displacement at 2.5 ft draft is 28,000 lb, while the latest estimates of "all-up" vessel weight total approximately 26,000 lb. On this basis, for protected waters operations such as rivers and harbors where the 3 ft depth limit is applicable, approximately 2,000 gallons of oil can be accommodated in the hulls for short-term storage. On the open seas where greater draft can be permitted, more oil can be stored, approximately 5,000 gallons per additional one foot of draft.

After establishing the hull lines, propulsion power requirements were computed as a function of vessel speed. These are shown in figure 37, and it can be seen that the effective horsepower required at 12 knots (the required non-harvesting speed capability) is 170 hp. This led to the selection of two 115 hp outboard engines to provide the required power.

After selection of the engines, refined estimates of other equipment weights and their locations aboard the vessel were determined by preparation of the general arrangement drawing shown in figure 38. It was deemed necessary to conduct some preliminary structural design and analysis of the hull and bridge structure in order to verify the weight estimates for these major items. The results of these structural design steps are shown in figures 39 and 40. Two points should be noted here - the bridge beams were designed on the basis of handling loads incurred while lifting the assembled vessel during launch or recovery. It was assumed that the "worst case" structurally would be inadvertent lifting from two points, at the bow end of one hull and the aft end of the other. It was deemed that this mode would be far more severe than any waterborne loadings, since even in rough waters, some distribution of loading would occur. The other point to note is that by integrally molding aluminum angle longitudinal stringers into the inside surface of the fiberglas hull skin, the hull is sufficiently strengthened to act as an oil storage tank itself. The bridge beams as shown are only representative of the overall weight and stiffness required. The final design will utilize a different arrangement to also provide support for the deck panels.

SECTION VII

VESSEL RESPONSE CHARACTERISTICS

With the catamaran size, configuration, weight, and weight distribution established it was possible to proceed with essential preliminary analysis of the vessel response to wave action. Figures 40 and 41 show the heave and pitch amplitude and phase response as a function of water wave length at a vessel speed of 3 knots. These data were computed using a digital computer program available at the Davidson Laboratory of Stevens Institute. The program is one normally used for mono-hull analysis, and its accuracy has been rigorously demonstrated for this type of hull. The program's accuracy when applied to catamarans is less certain, because of possible interference effects due to the proximity of the two hulls. Unfortunately, empirical data is not available to check the results of these computed responses. It is unlikely that the data are sufficiently in error to change the main conclusion to be drawn, however. Since normalized values of heave and pitch amplitude are plotted, the ideal situation for the oil recovery catamaran is to achieve values of 1.0, indicating that the vessel follows the water surface precisely. The data show that this situation is not approached in pitch or heave except for wave lengths of 60 ft or greater. These long wave lengths can be expected in unprotected waters in the open ocean, but not in protected waters. Even for the long wave lengths the amplitude ratios are not sufficiently close to unity to state that the vessel will follow the water within the few inches required.

This led to the conclusion that the OPU must be decoupled from the vessel in heave and surge. Decoupling in pitch is not considered necessary at this time since the OPU entrance will be located at the same longitudinal station as the vessel center of gravity.

One undesirable characteristic which is a by-product of a vessel design which has good surface tracking characteristics is high accelerations. These have been computed to fall in the range of 1.5 g upward and 0.6 g downward in heave for sea states of four to five at a vessel speed of 3.4 knots. In a sea state three situation, closer to the specified rough sea environment, the accelerations are 1.12 g up and 0.7 g down. This certainly implies considerable personnel discomfort at times, and the decoupling of the OPU also serves to apply remedies for this problem. By storing more oil to appropriately increase the vessel draft, these accelerations can be reduced. Although this deteriorates water surface following properties, the decoupling of the OPU makes this less important.

Due to limitations in time and budget, no analysis was conducted to assess roll and yaw response. The catamaran configuration possesses excellent inherent response characteristics for these motions, and these were deemed to be of lesser priority for dynamic analysis at this stage. The same can be said of coupled vessel motions although these must be given proper attention in the following phases of the program.

Catamaran Vessel Design

The catamaran configuration and sizing have been reasonably well defined, along with the most important response characteristics, heave and pitch. The concept of decoupling the OPU in heave and surge has served to relieve somewhat the stringent catamaran hull response requirements, although roll, yaw and coupled responses need further examination.

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OPU Design

Sufficient data has been obtained to allow more detailed full-scale design of the oil recovery, flotation, and motion decoupling elements of the OPU. The response analysis of the decoupled OPU as presented in the Appendix has shown a favorable water surface following characteristic for water wave lengths of 40 ft or greater. For shorter wave lengths it will be necessary to rely on the oil film to provide damping of the wave motions ahead of the OPU. The rough water experiments with the model have certainly served to point out the powerful damping of the oil film, and Mollo-Christensen of M.I.T. has reported similar behavior in that he shows significant reductions in the power density spectra produced by an oleyl alcohol film on water for wave lengths shorter than 35 ft (*). The debris screens to be installed between the catamaran hulls near the bow can also contribute significantly to high-frequency wave damping by judicious design.

The use of a servo control to maintain the foil in position ahead of the OPU entrance will assure achievement of the "fine-grained" control required.

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* "Physics of Turbulent Flow", by Dr. Erik Mollo-Christensen, Massachusetts Institute of Technology. Presented at the American Institute of Aeronautics and Astronautics 7th annual meeting, Houston, Texas, October 1970.

SECTION VIII

ACKNOWLEDGMENT

The Physical Science Laboratory wishes to acknowledge the contributions of Dr. John P. Breslin, Director, Davidson Laboratory, Stevens Institute of Technology, especially his participation in the catamaran preliminary design and dynamic response analysis.

SECTION IX

SYMBOLS

V_b	Linear belt speed ∿ ft/sec
V_m	Model speed ∿ ft/sec
β	Angle between model plate wetted surface and vertical plane ∿ degrees
α	Angle between hydrofoil chord plane and model plate wetted surface - positive when leading edge below wetted surface plane ∿ degrees
z	Oil thickness ahead of model ∿ inches
h	Belt-plate gap ∿ inches
t	Duration of test run ∿ seconds
ΔP	Differential pressure-side or center orifices ∿ m m H_2O
T	Oil temperature ∿ degrees centigrade
V_a	Volume of oil available for recovery during test run ∿ in.^{3}
V_r	Volume of oil recovered during test run ∿ in.^{3}
E	Percent of oil removed = $V_r/V_a \times 100$
H	Wave height ∿ inches
L	Wave length ∿ inches
C	Wave celerity or propagational speed ∿ ft/sec
q_f	Quantity of fluid recovered during test run ∿ gallons
q_w	Quantity of water in recovered fluid during test run ∿ gallons
e	Percent water in recovered fluid = $q_w/q_f \times 100$
Q	Oil recovery rate, gal./sec
Q'	Oil recovery rate, ft^3/sec
W	Belt width, ft

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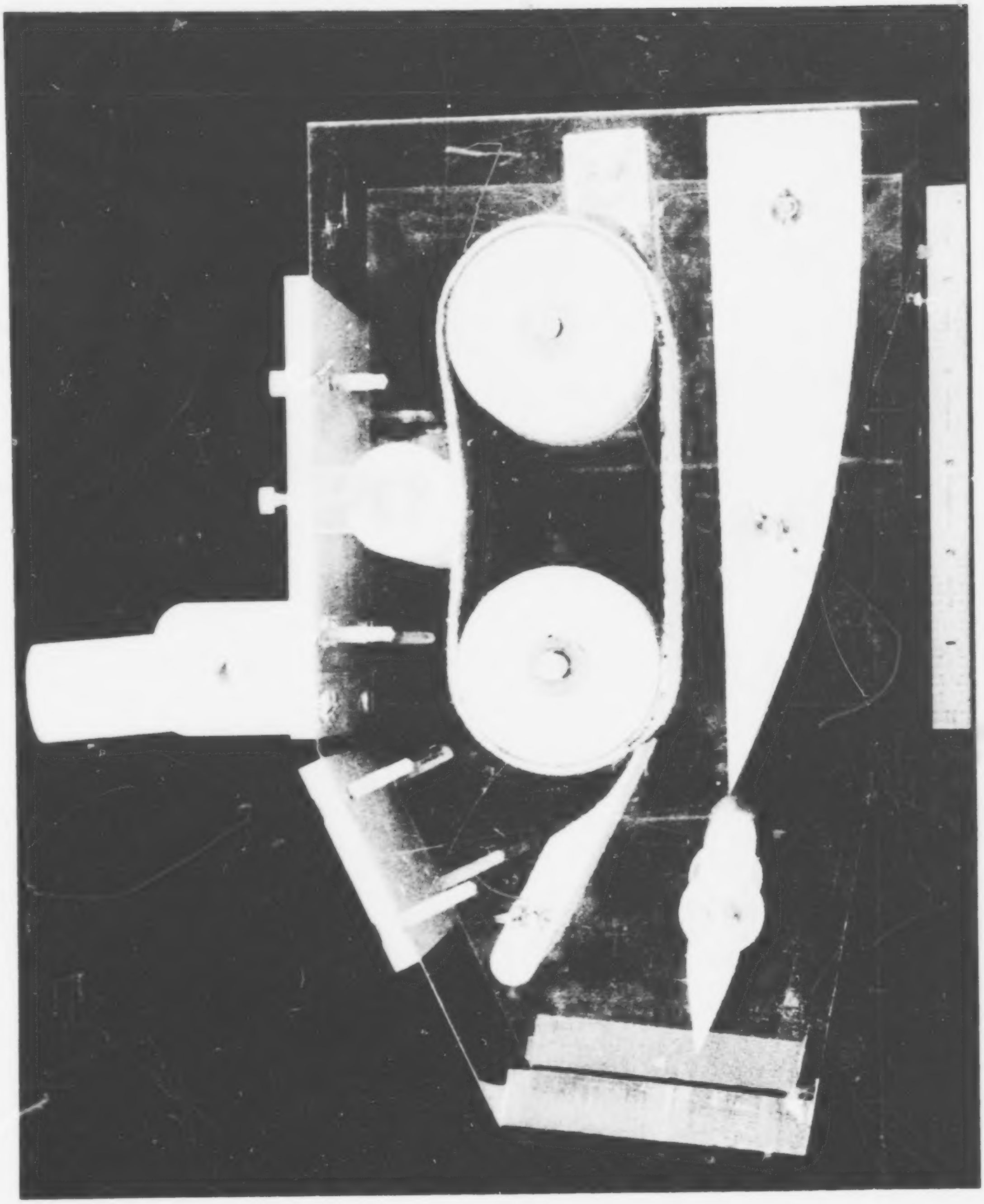

FIGURE 1 – OPU TEST MODEL

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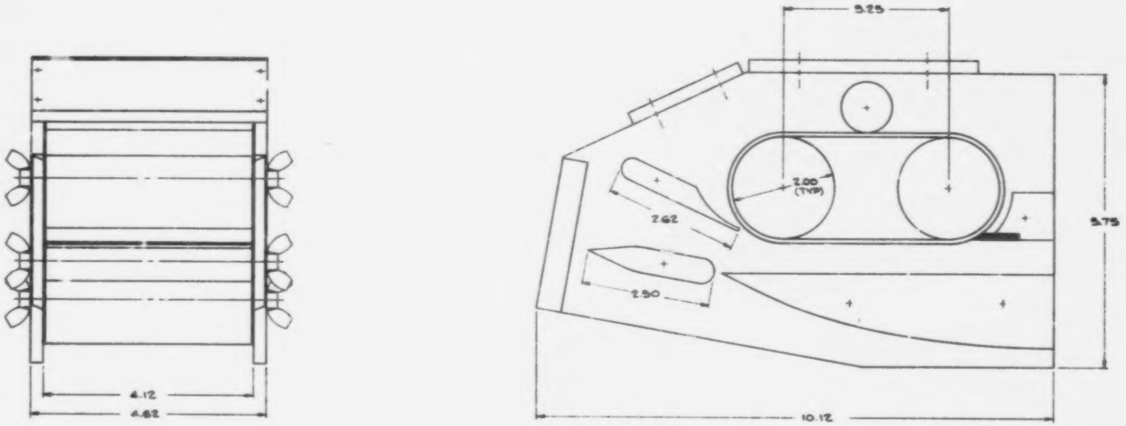

4.12
4.62
3.25
2.00 (TYP)
2.62
2.50
5.75
10.12

FRONT VIEW

SIDE VIEW
(SIDE PLATE REMOVED)

FIGURE 2 – OPU TEST MODEL

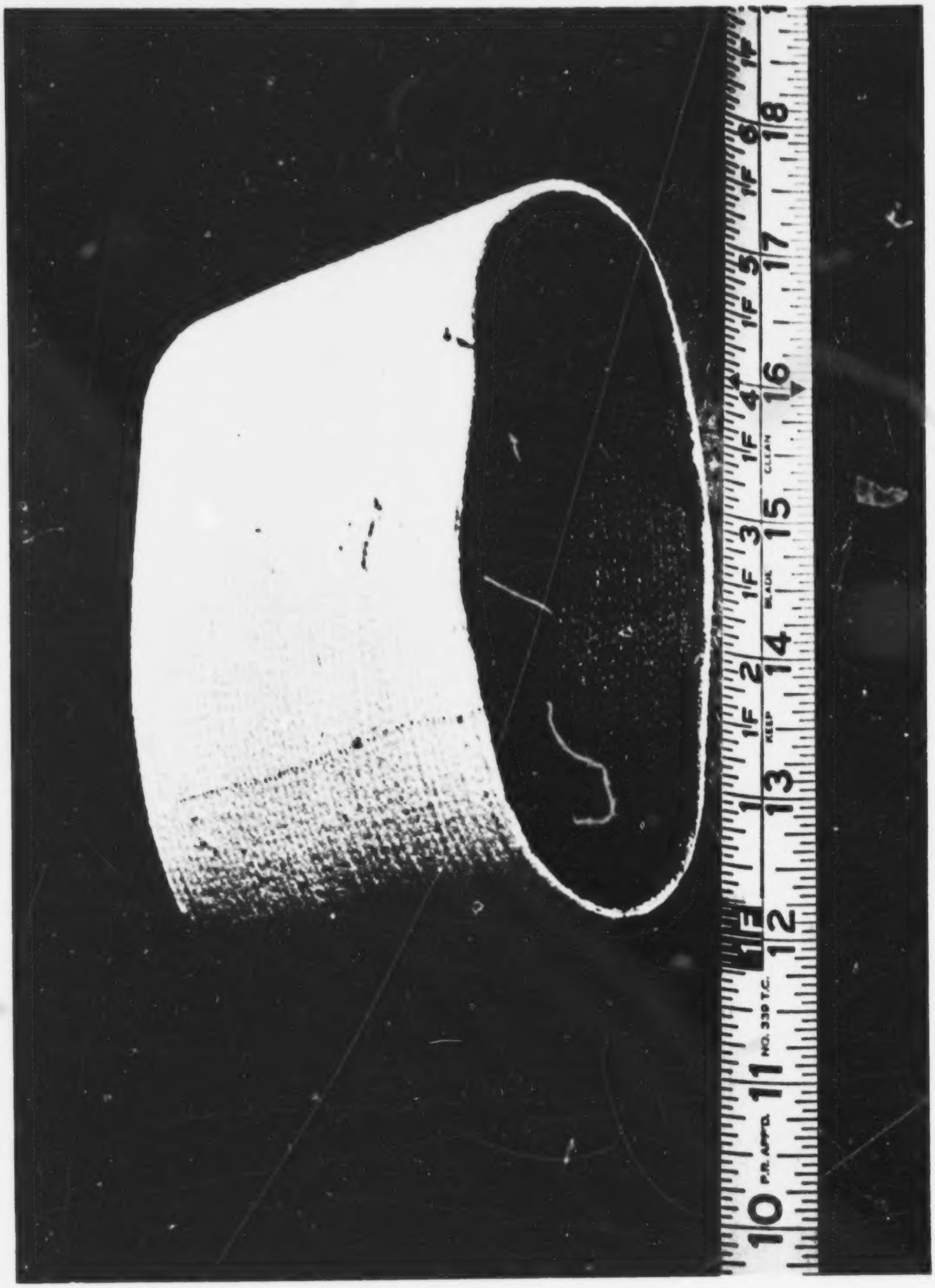


FIGURE 3 – OPU TEST MODEL BELT

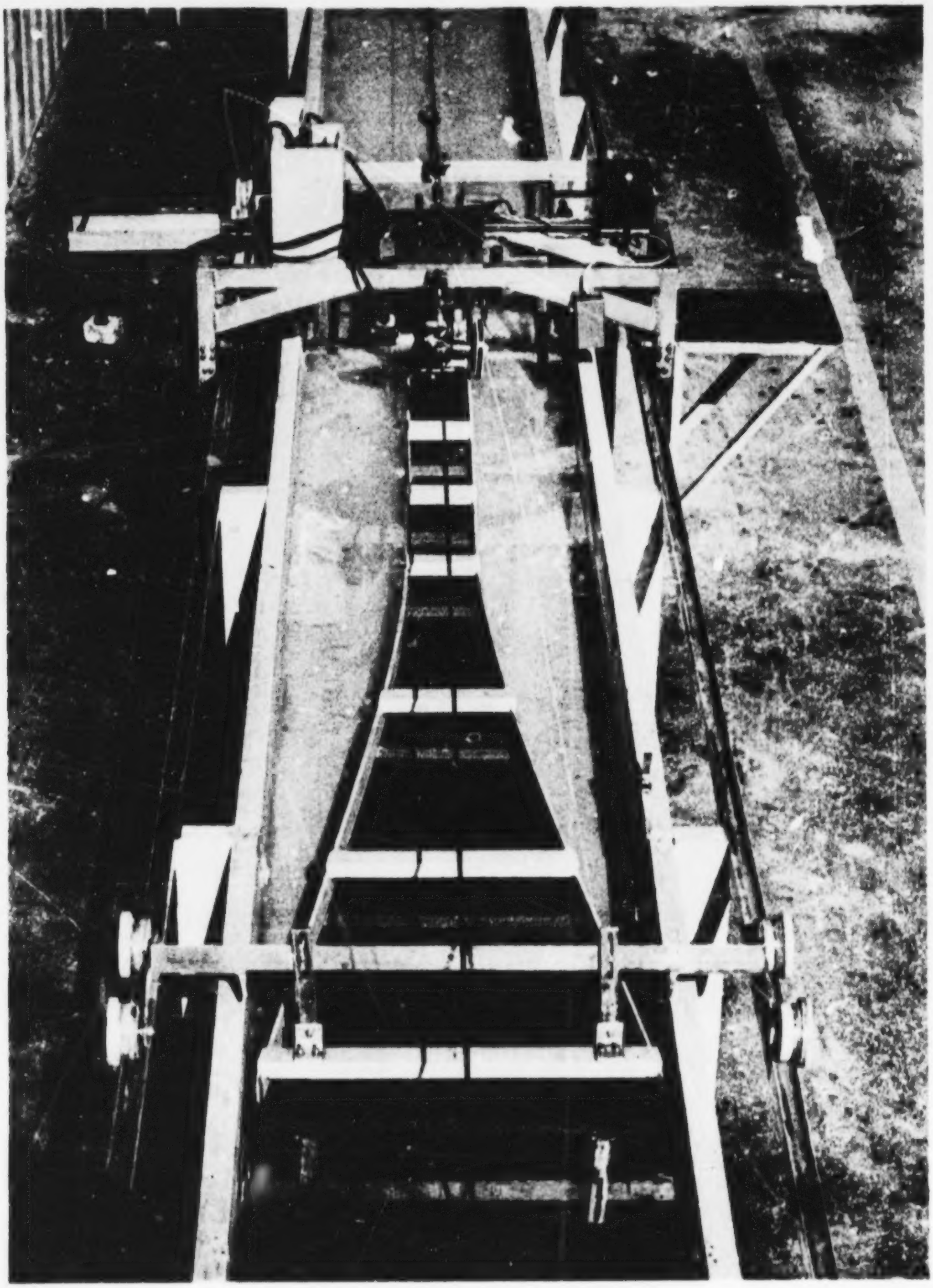


FIGURE 4 – OPU TEST MODEL WITH BOOM

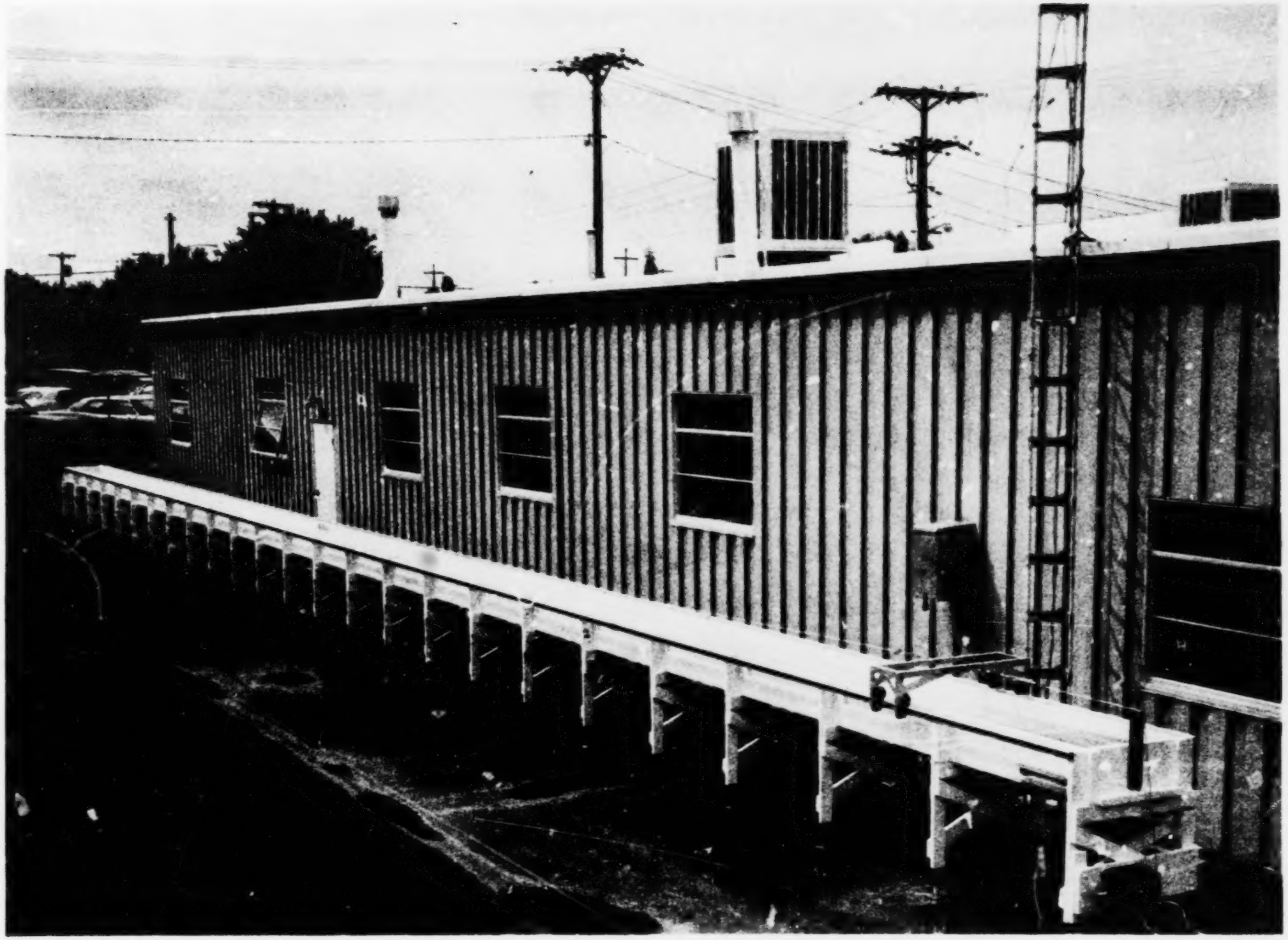


FIGURE 5 – OPU TEST CHANNEL

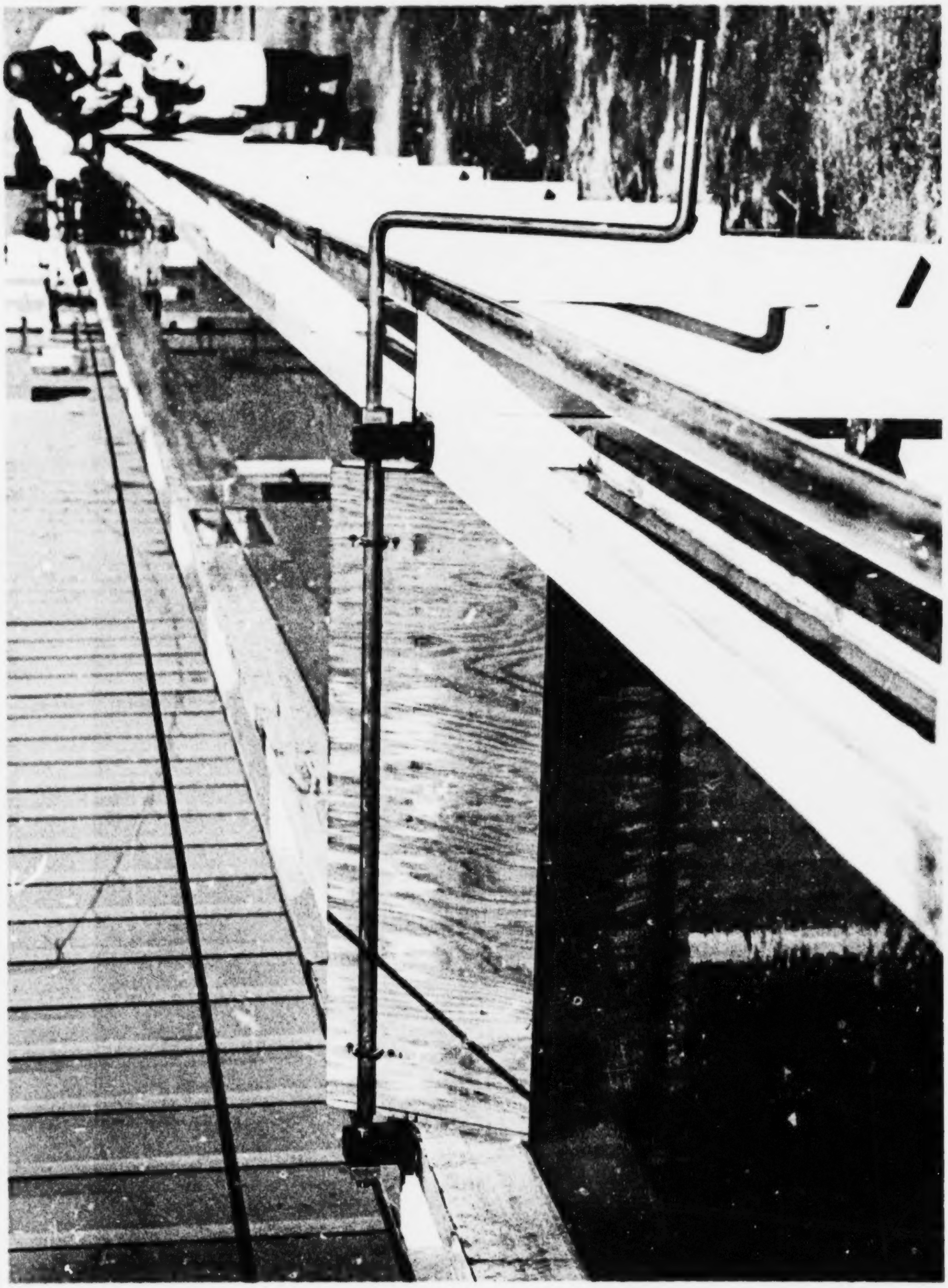


FIGURE 6 – TEST CHANNEL WAVE PADDLE

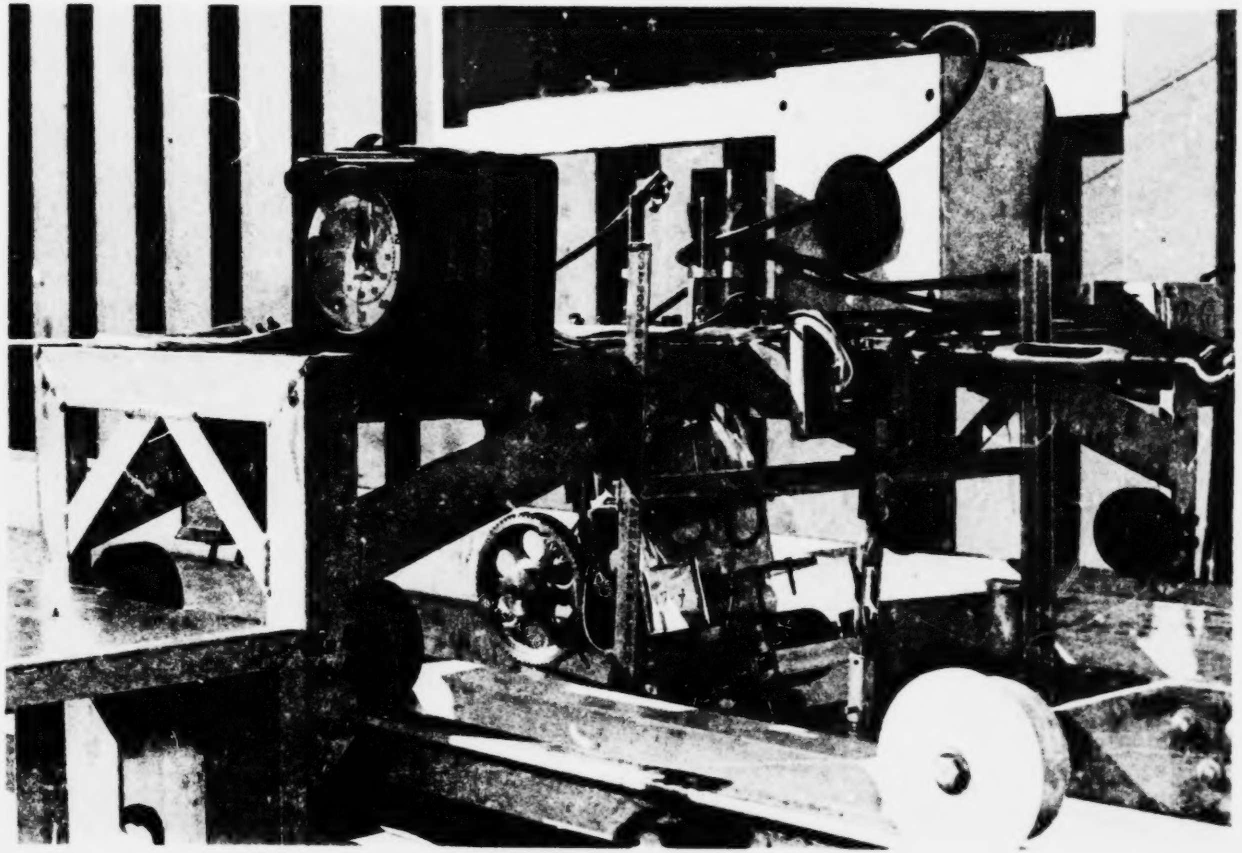


FIGURE 7 – OPU TEST MODEL CARRIAGE

OPU TEST MODEL PRESSURE
ORIFICES AND SYMBOLS

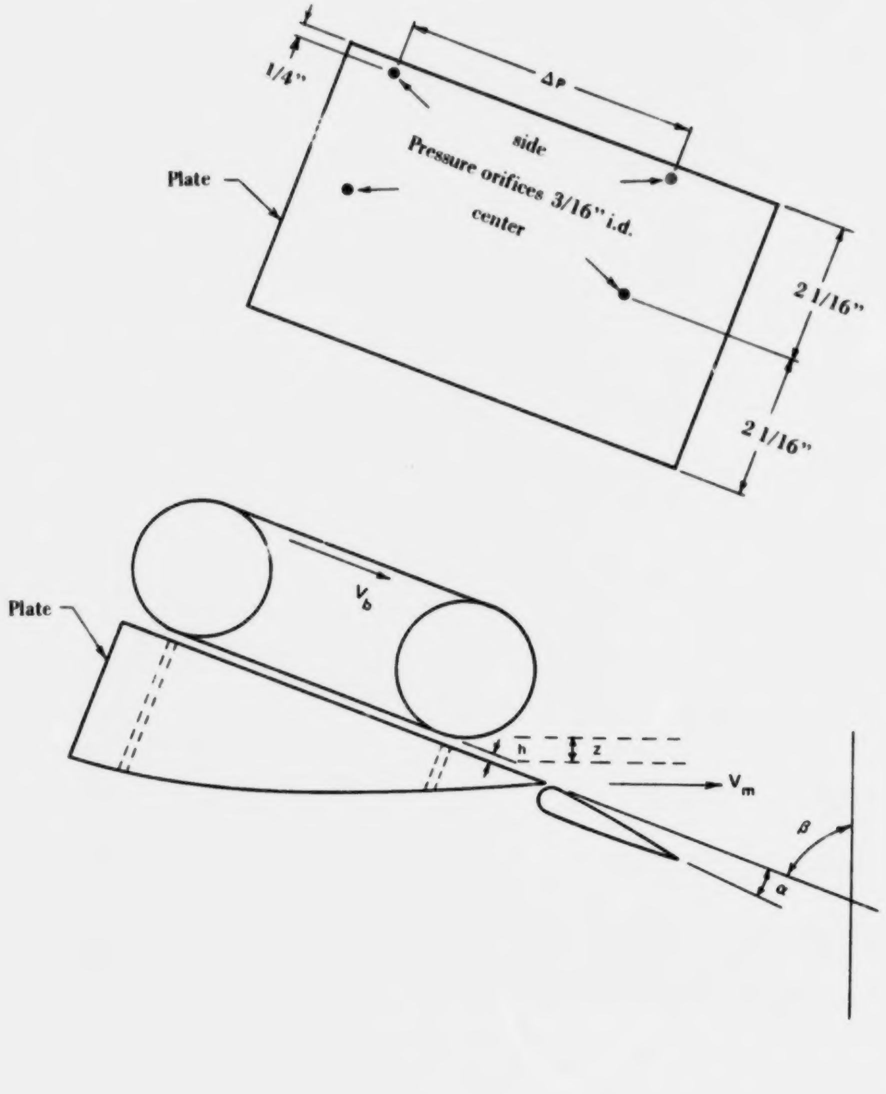

1/4"
Δp
side
Pressure orifices 3/16" i.d.
center
Plate
2 1/16"
2 1/16"
Plate
V_b
h
z
V_m
β
α

FIGURE 8 – OPU TEST MODEL AND SYMBOLS

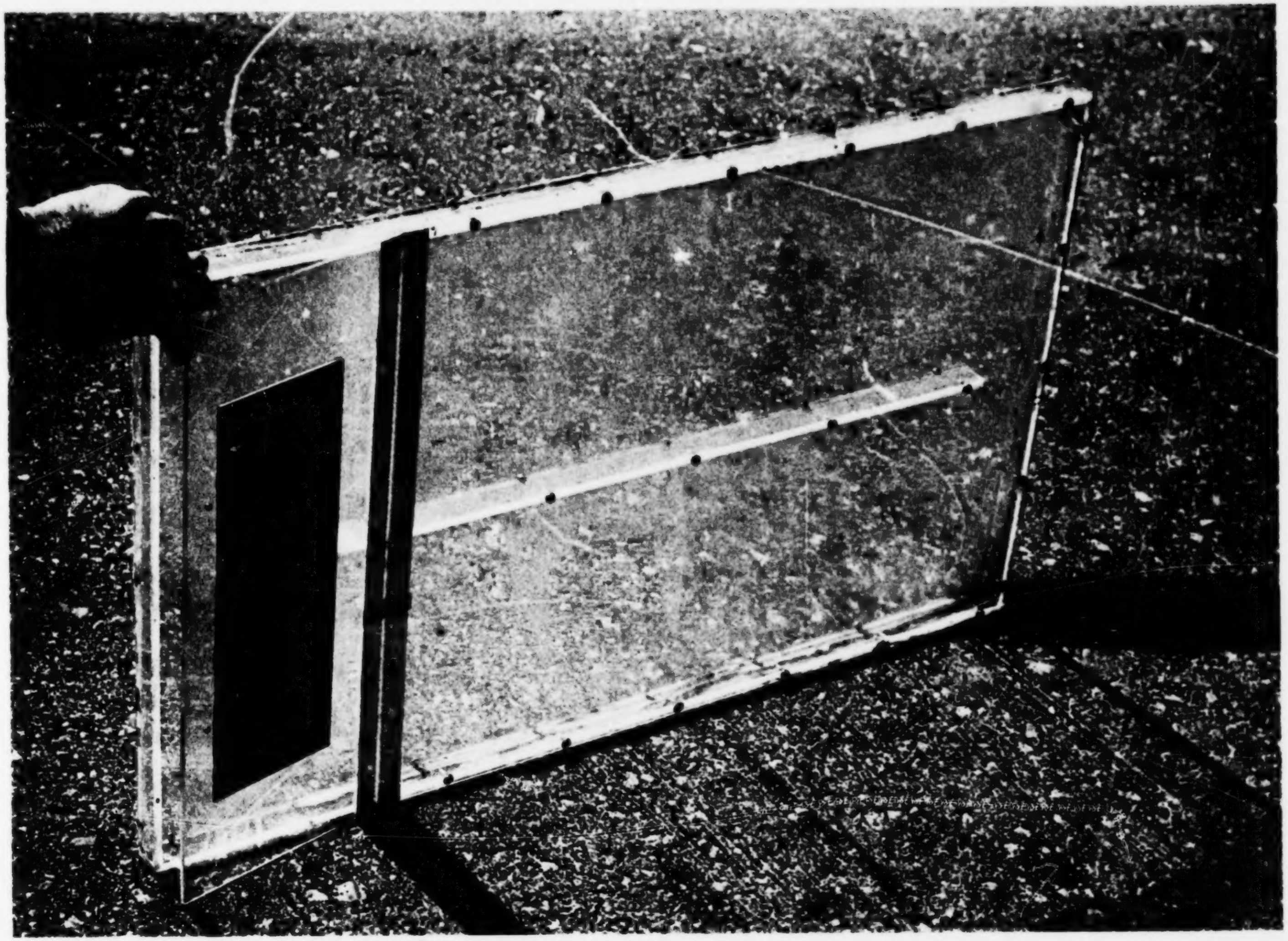


FIGURE 9 – OIL TEST SAMPLE BOX

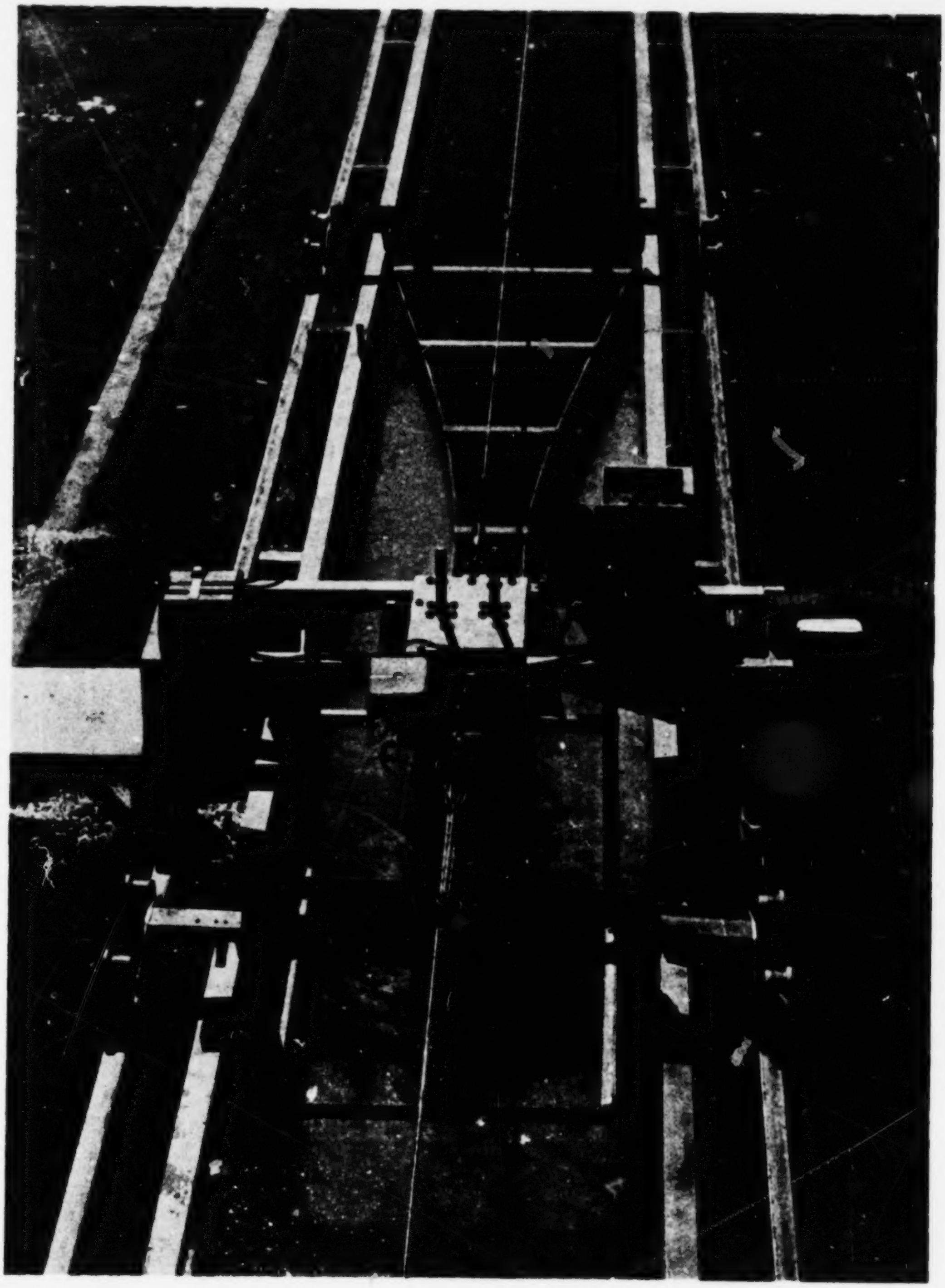


FIGURE 10 – OPU TEST MODEL CARRIAGE & SAMPLE BOX FRAME

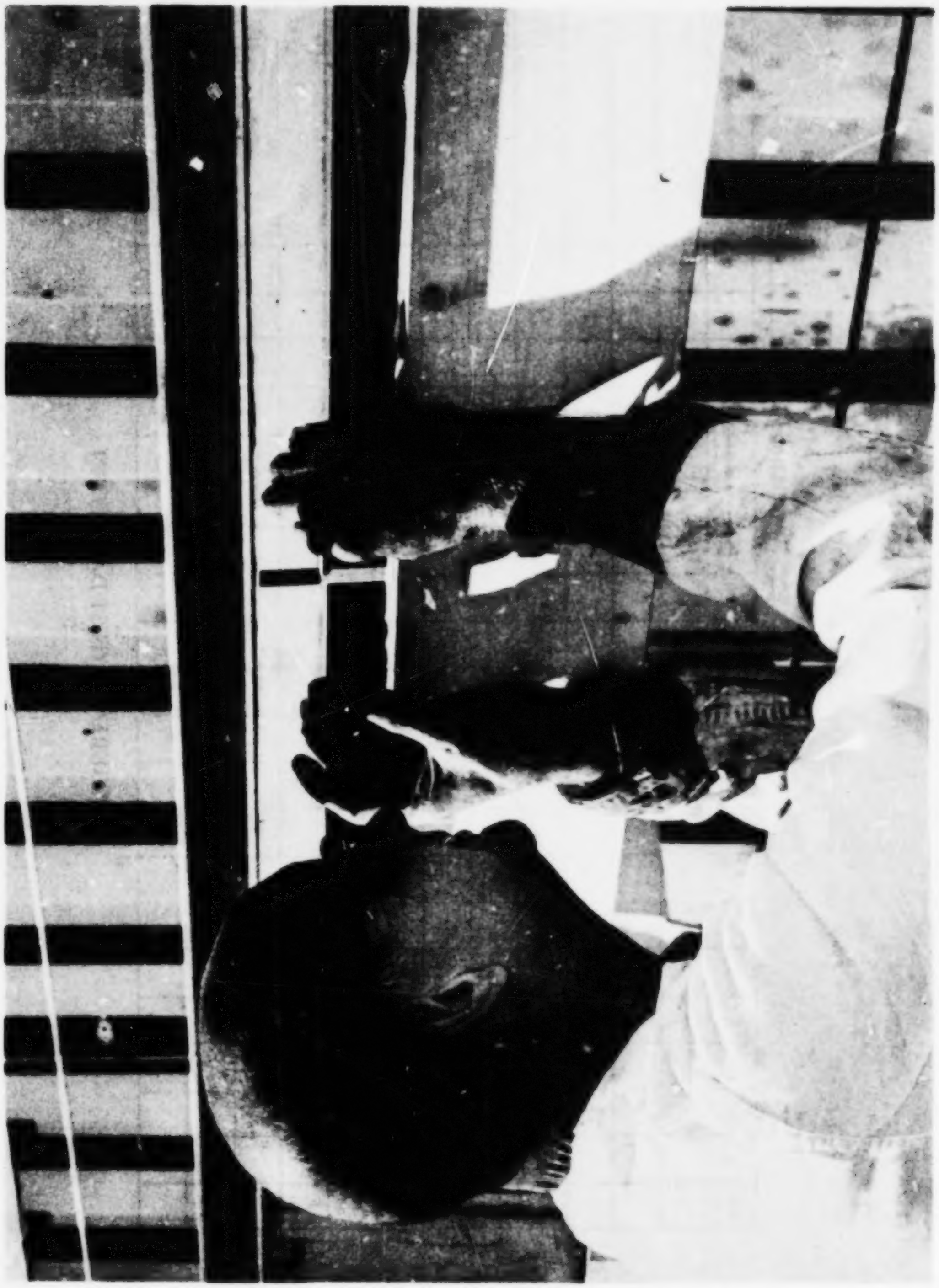


FIGURE 11 – OIL THICKNESS MEASUREMENT

OIL RECOVERY MODEL TESTS

DATA SHEET NO. ________

MODEL NO. ________ FLUID ________ VISCOSITY ________ SPECIFIC GRAVITY ________ DATE ________

WATER DEPTH ________ TEST RUN DISTANCE ________

RUN NO.	V_s	V_m	β	α	ℓ	h	t	Δp SIDE	Δp CENTER	T	V_a	V_r	E	WAVE			q_r	q_m	Q	ϵ	REMARKS
														H	L	C					

FIGURE 12 – TEST DATA FORM

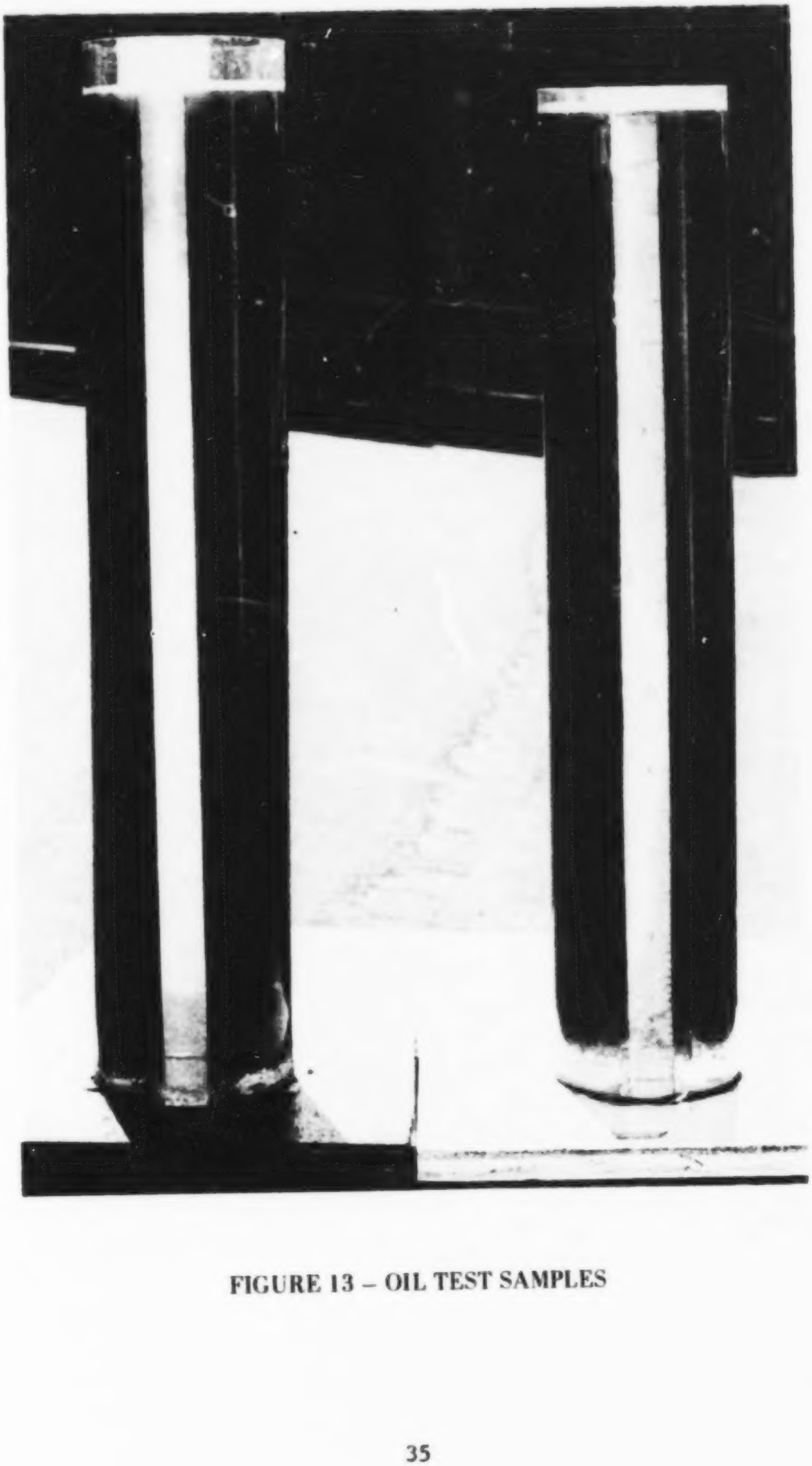


FIGURE 13 – OIL TEST SAMPLES

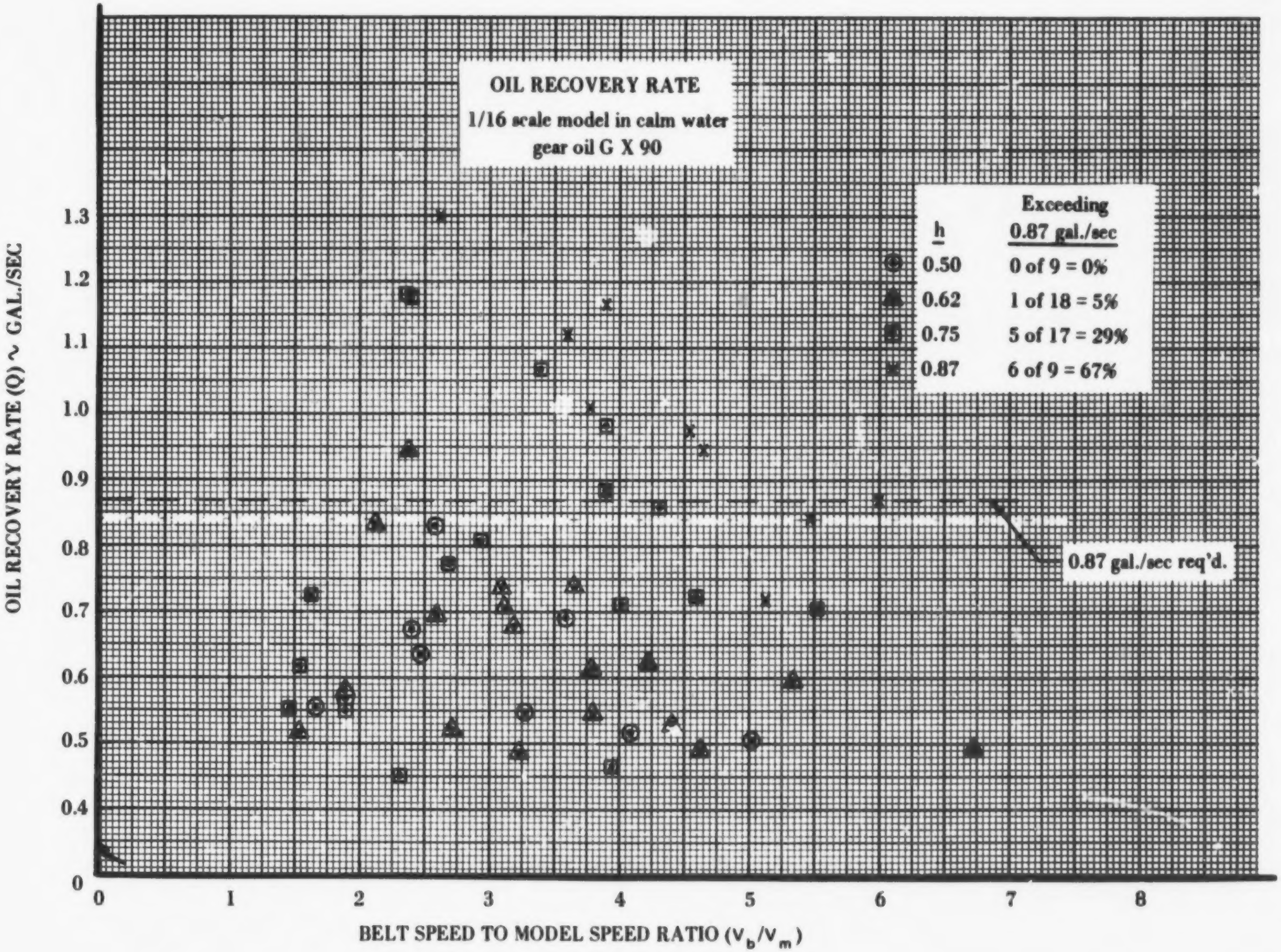


FIGURE 14 – OIL RECOVERY RATE

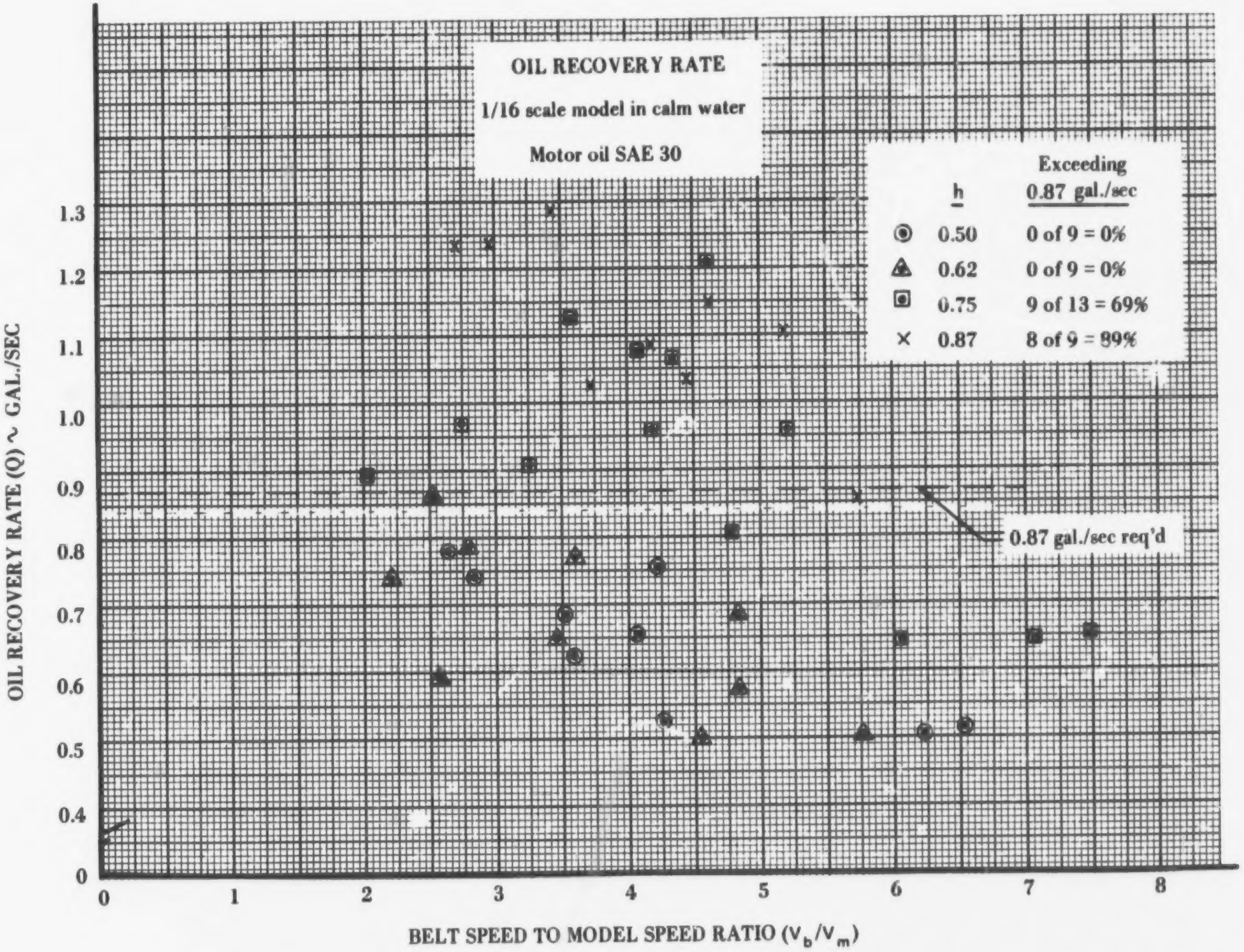


FIGURE 15 – OIL RECOVERY RATE

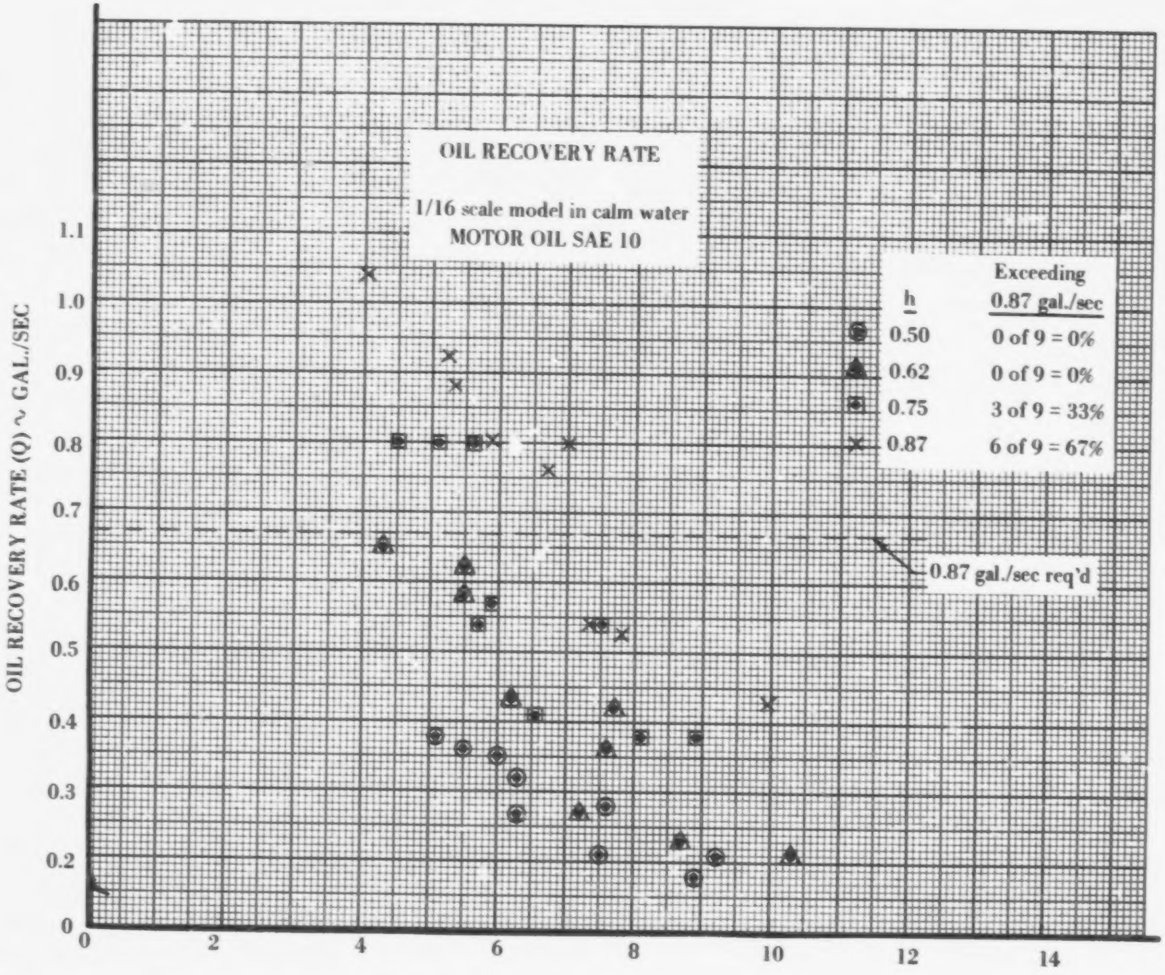


FIGURE 16 – OIL RECOVERY

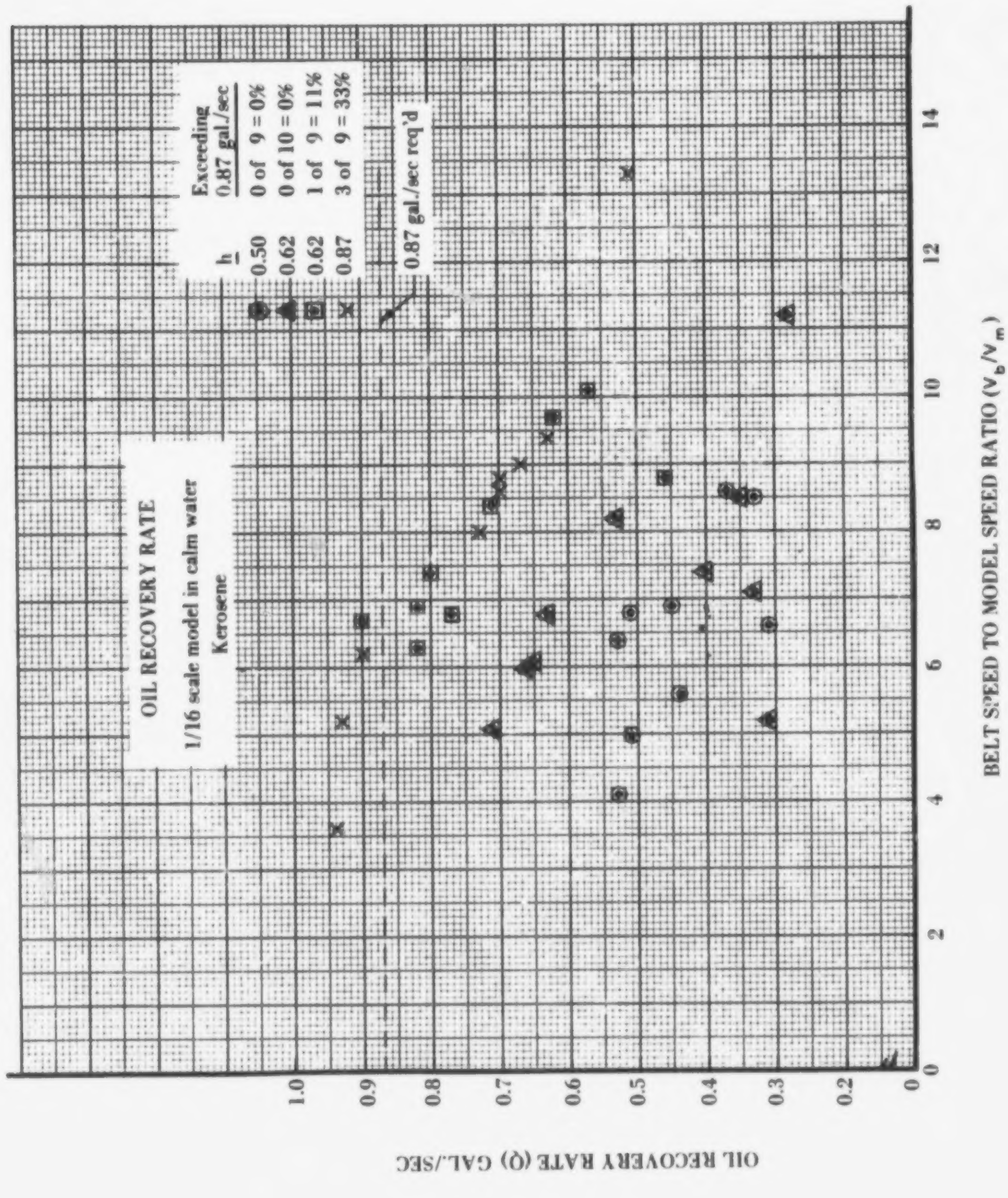


FIGURE 17 – OIL RECOVERY

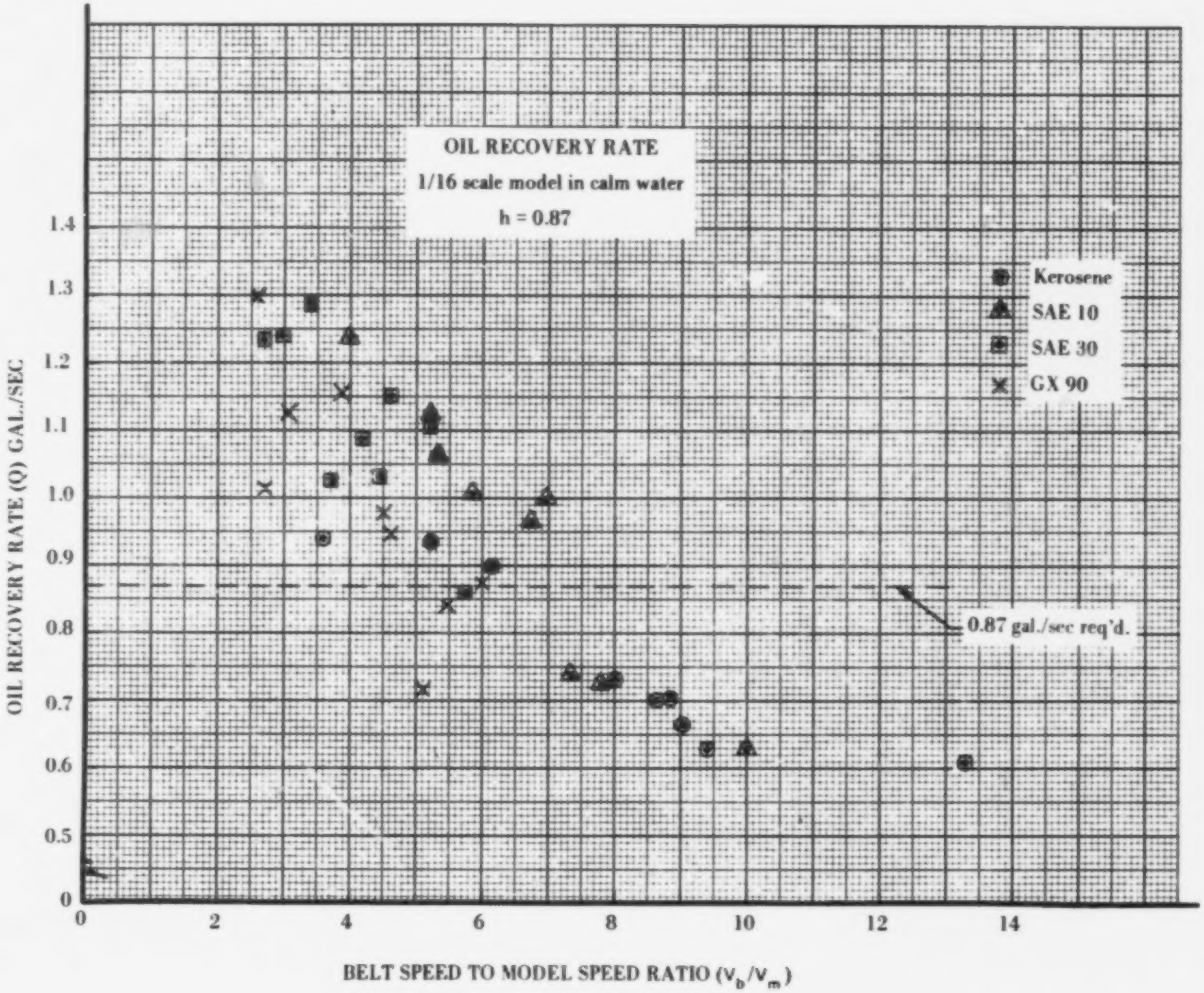


FIGURE 18 – OIL RECOVERY

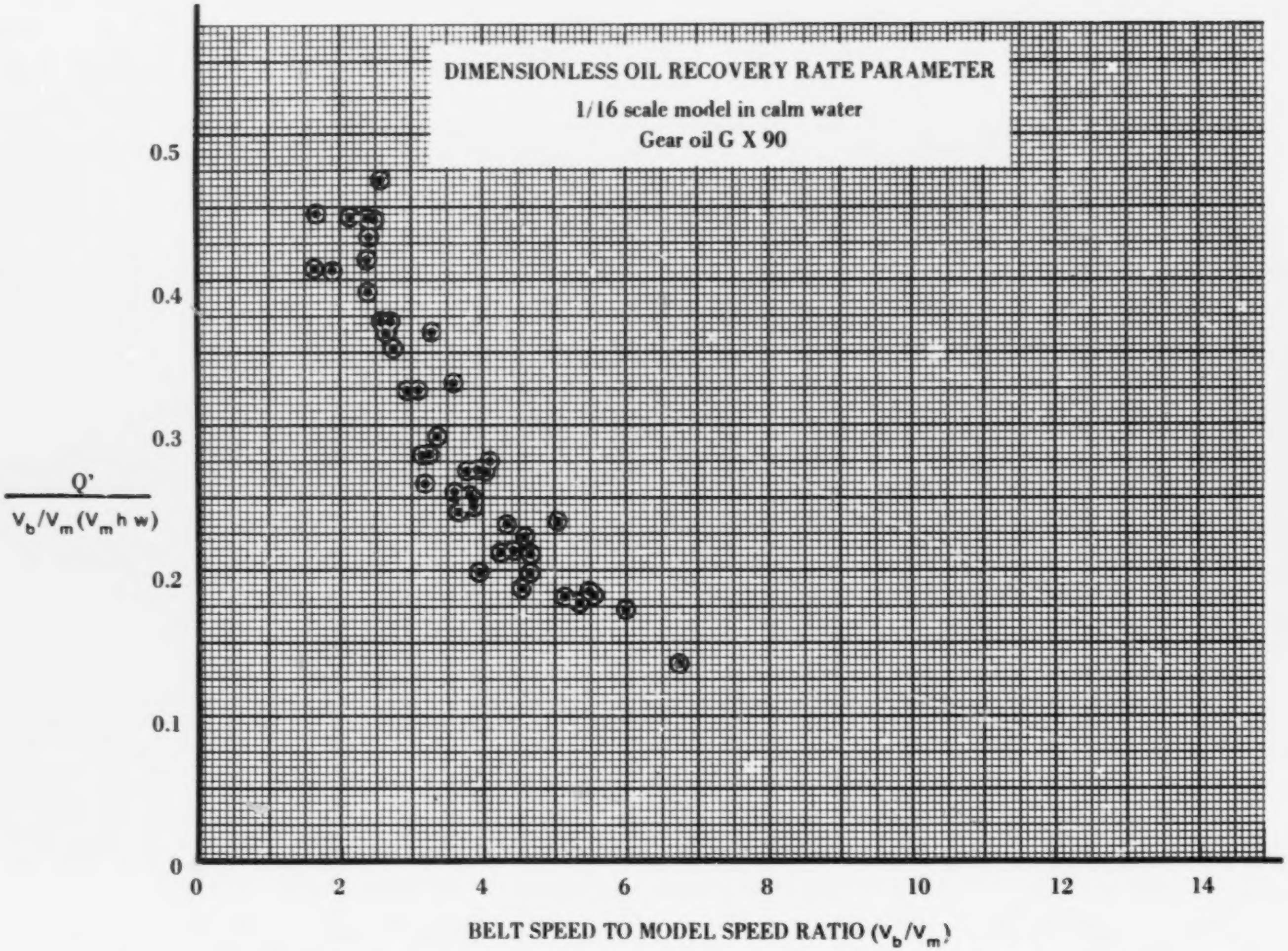


FIGURE 19 – DIMENSIONLESS OIL RECOVERY RATE PARAMETER

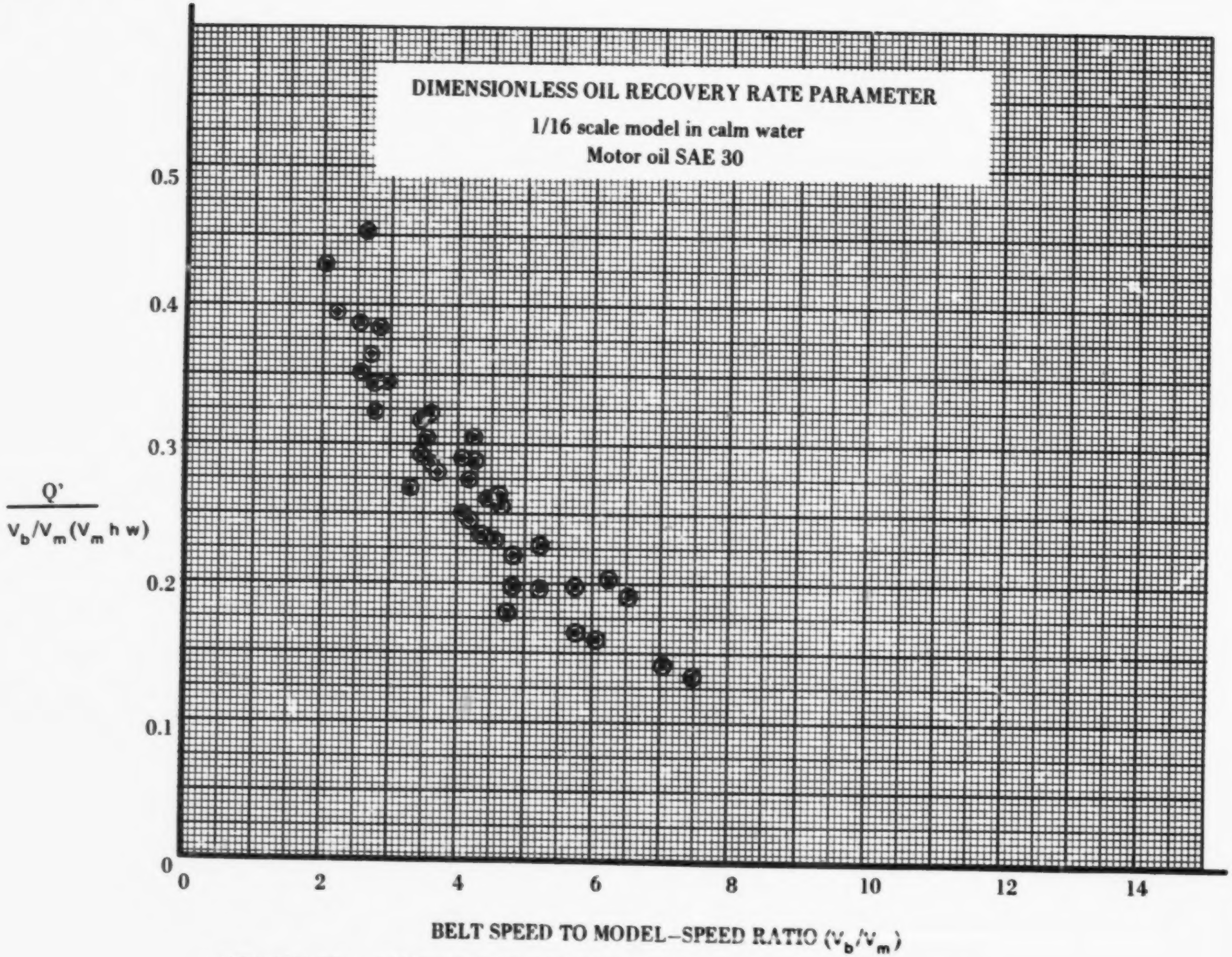


FIGURE 20 – DIMENSIONLESS OIL RECOVERY RATE PARAMETER

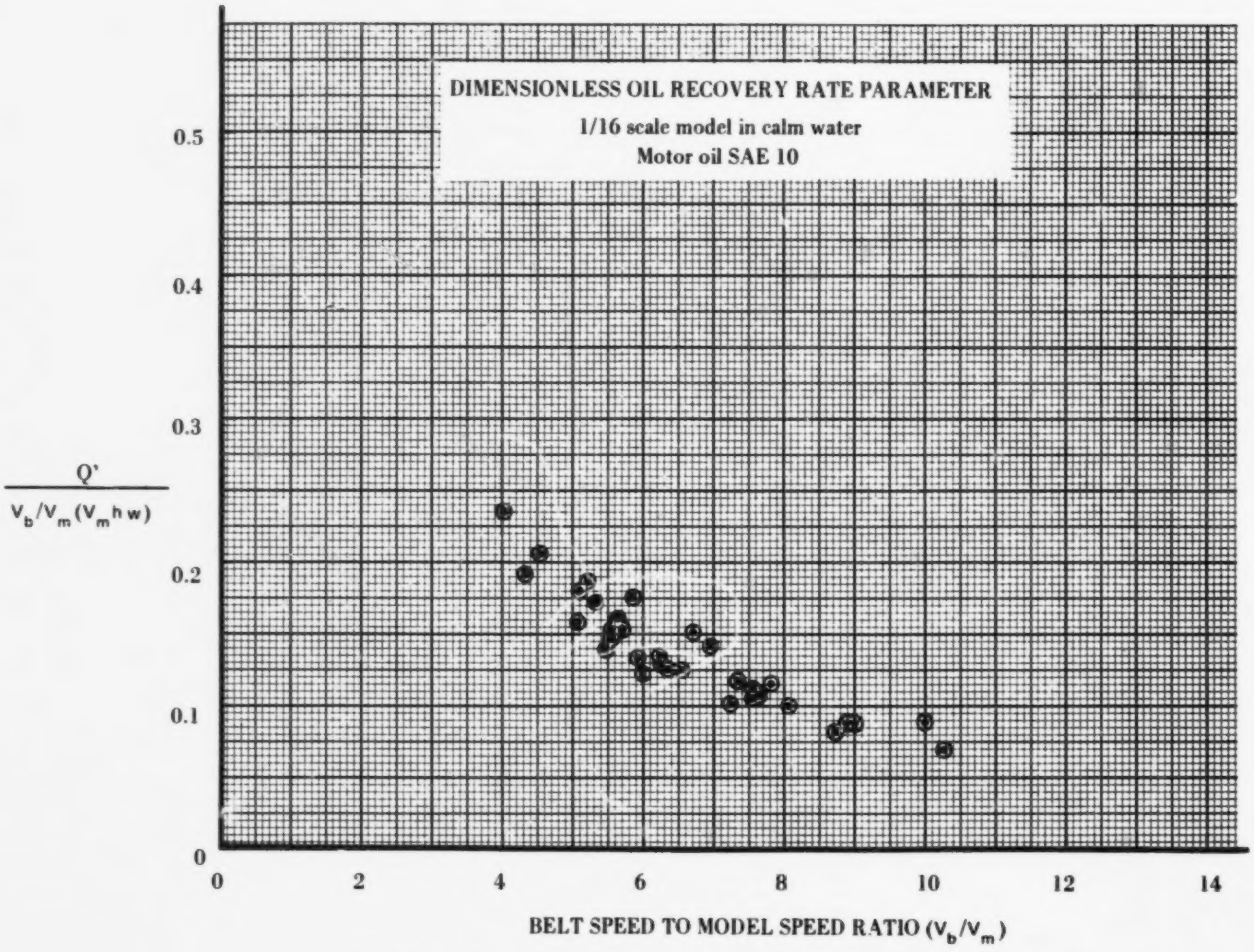


FIGURE 21 – DIMENSIONLESS OIL RECOVERY RATE PARAMETER

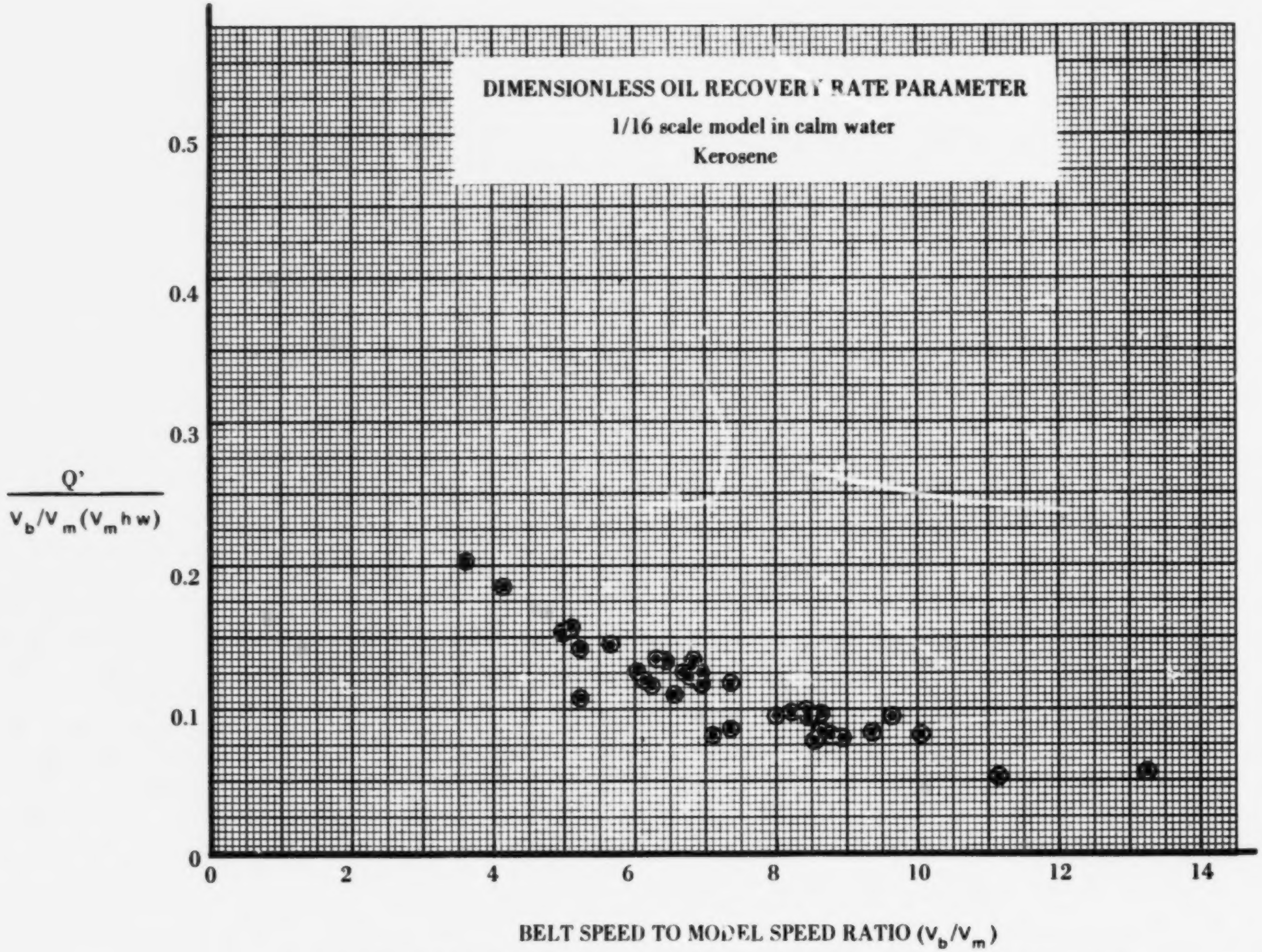


FIGURE 22 – DIMENSIONLESS OIL RECOVERY RATE PARAMETER

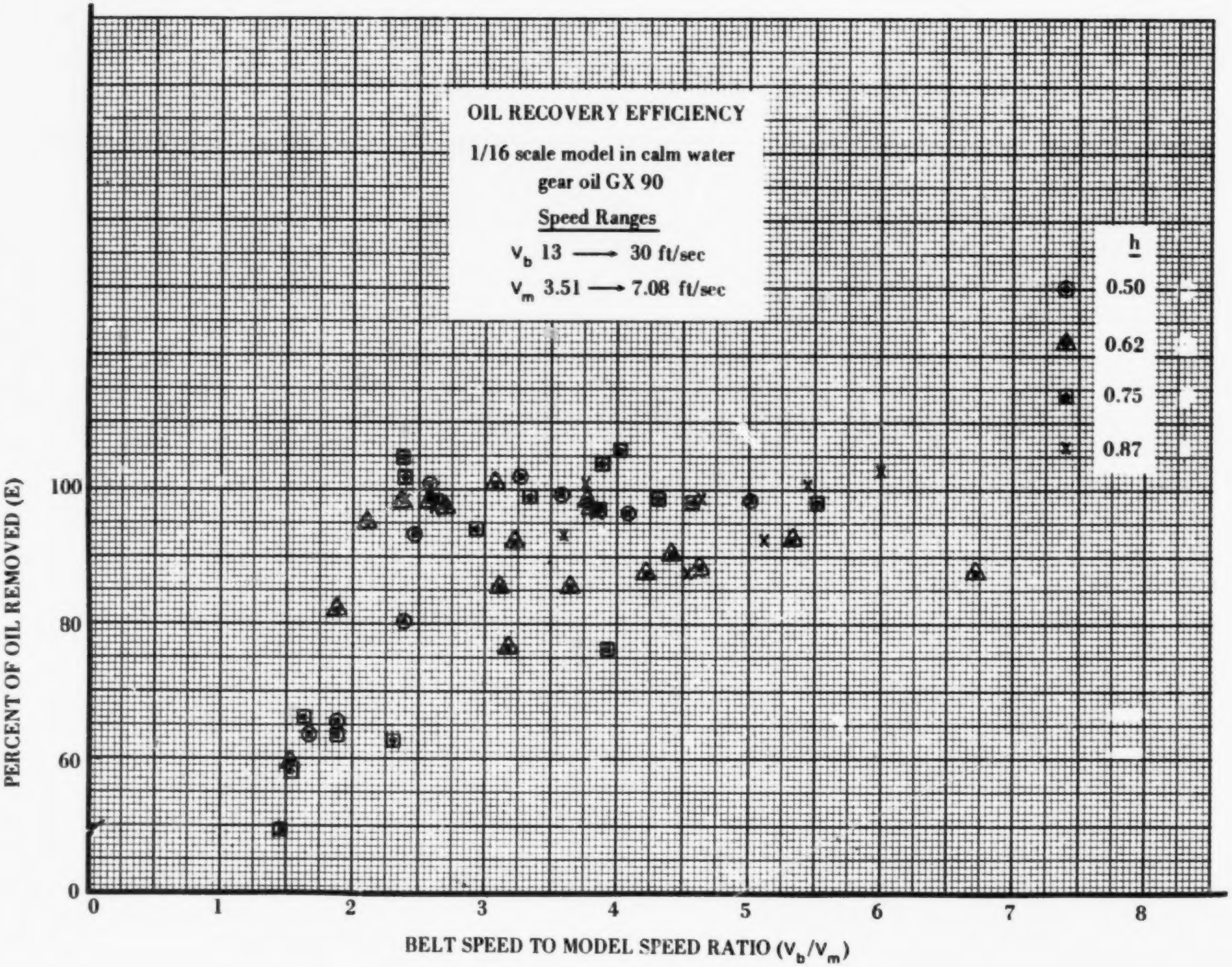


FIGURE 23 – OIL RECOVERY EFFICIENCY

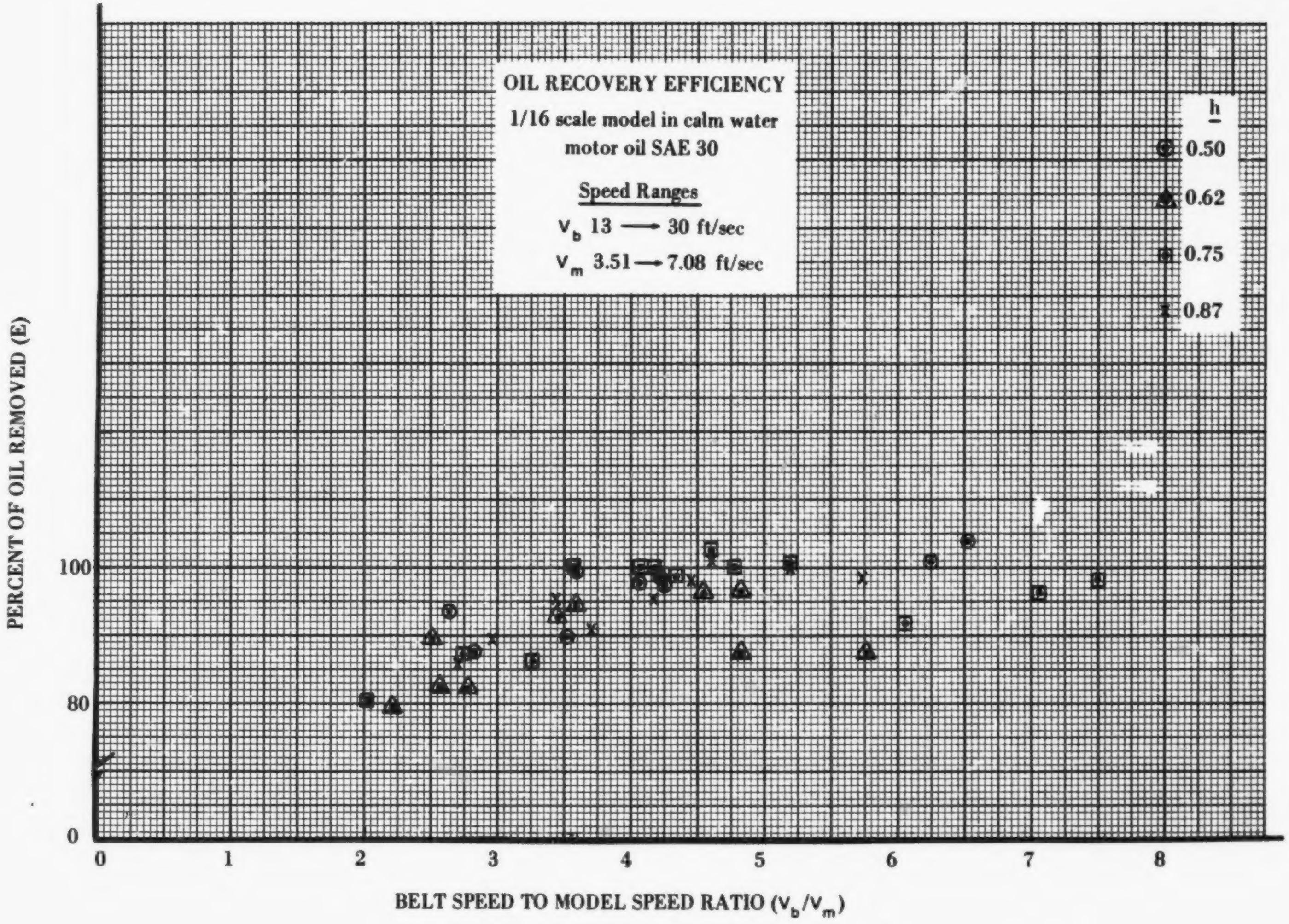


FIGURE 24 – OIL RECOVERY EFFICIENCY

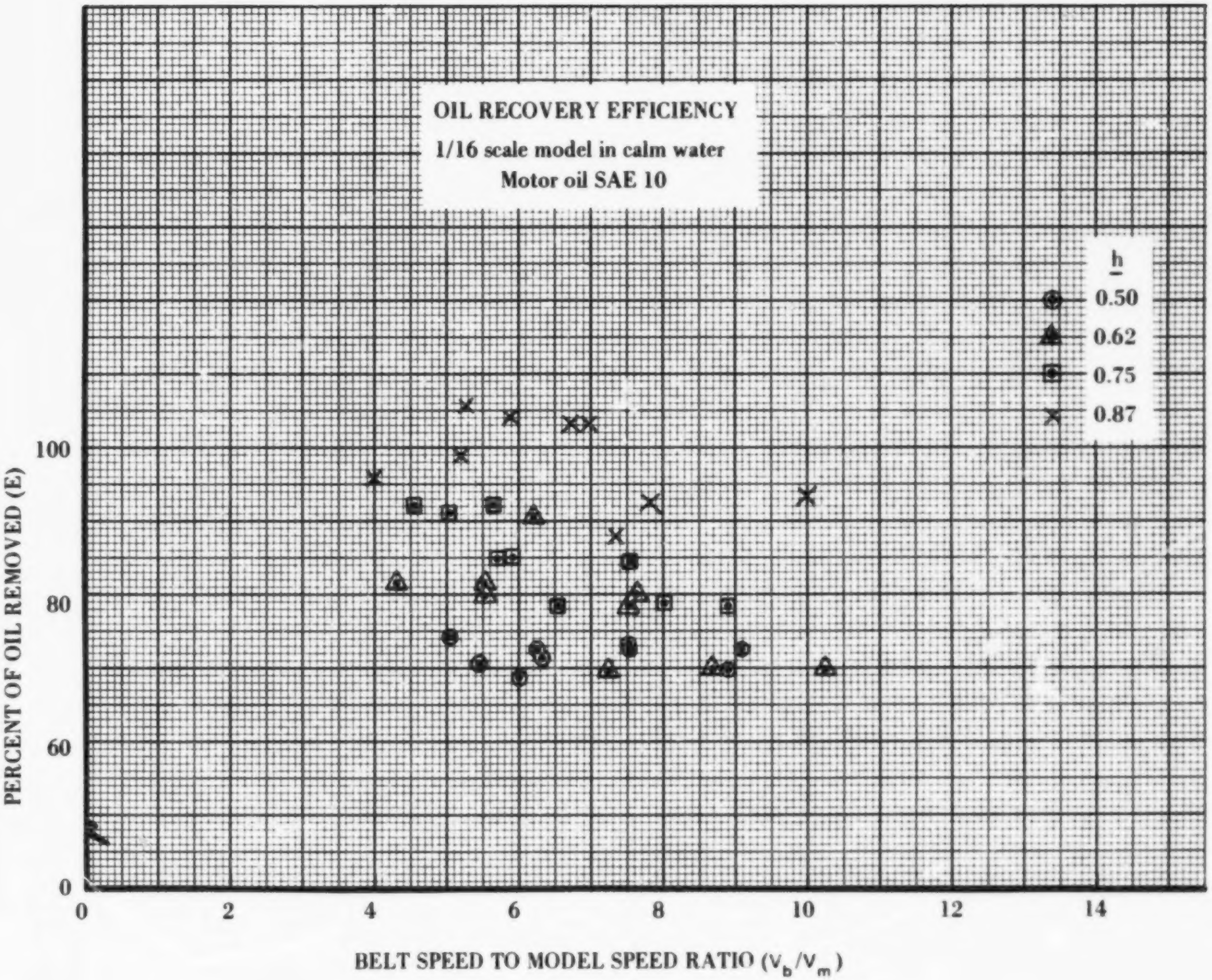


FIGURE 25 – OIL RECOVERY EFFICIENCY

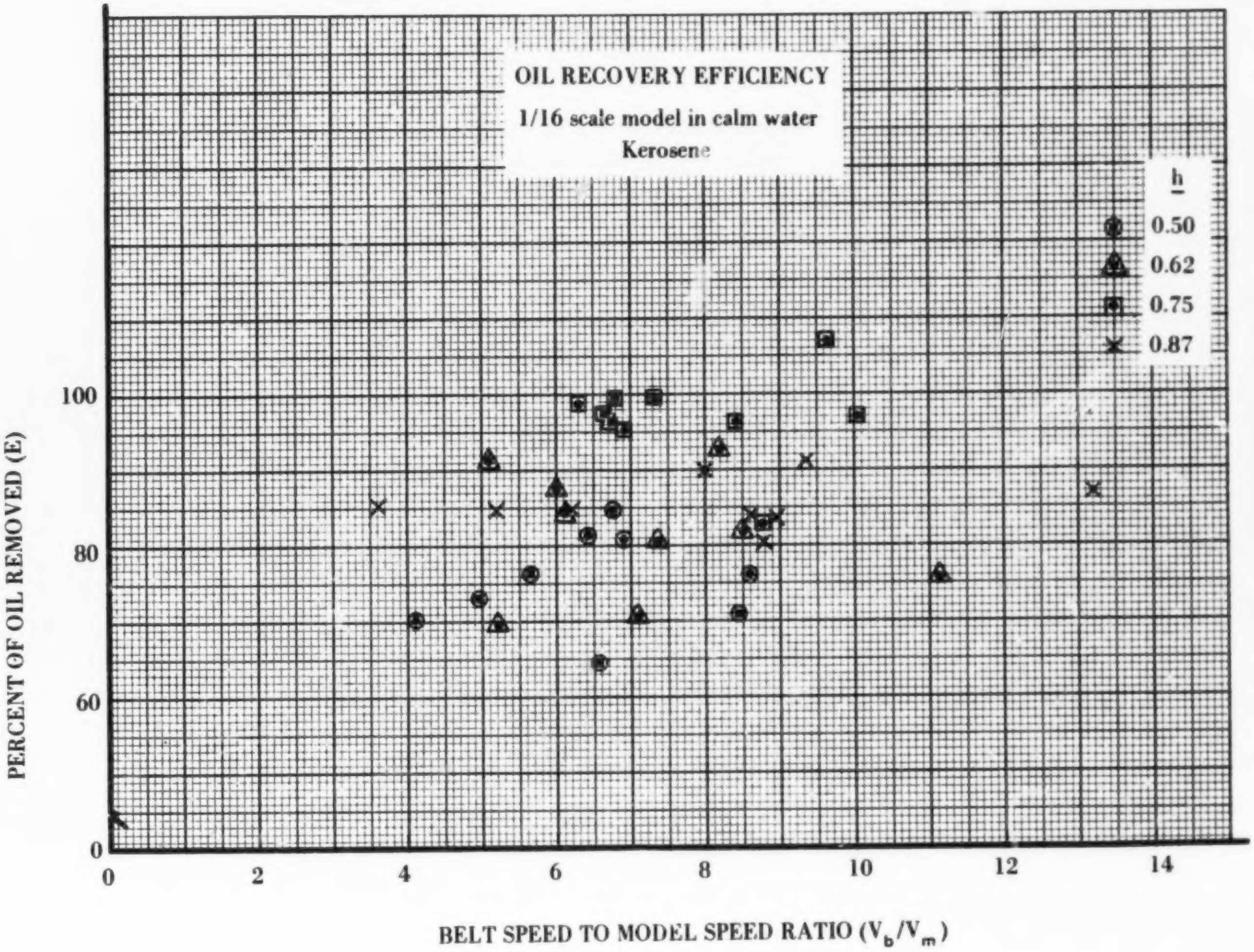


FIGURE 26 – OIL RECOVERY EFFICIENCY

OPU TEST MODEL
(top view)

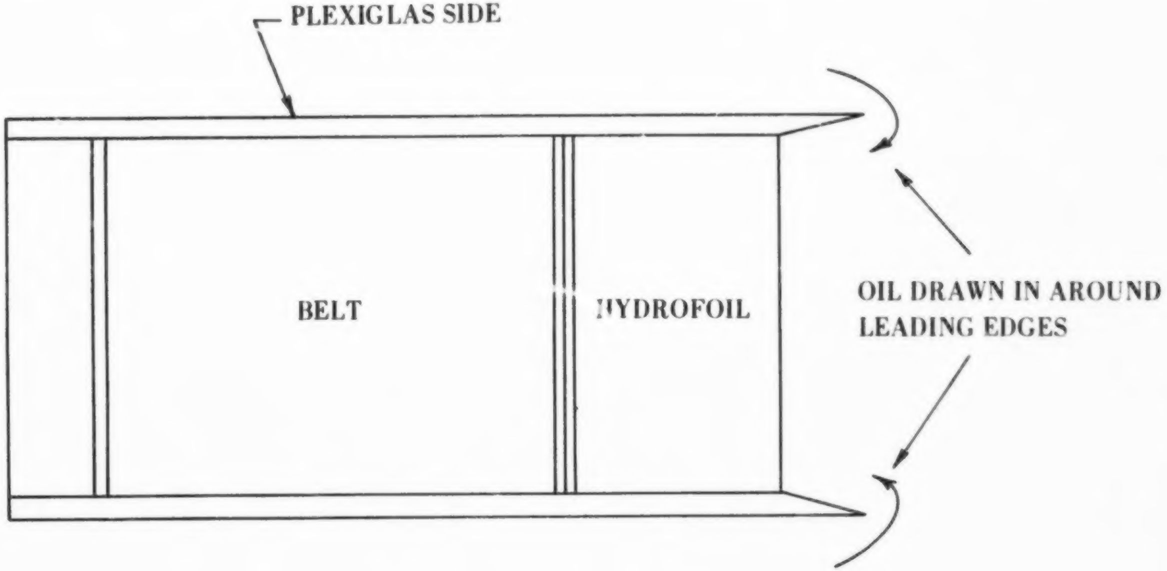

PLEXIGLAS SIDE
BELT
HYDROFOIL
OIL DRAWN IN AROUND
LEADING EDGES

FIGURE 27 – OPU TEST MODEL (TOP VIEW)

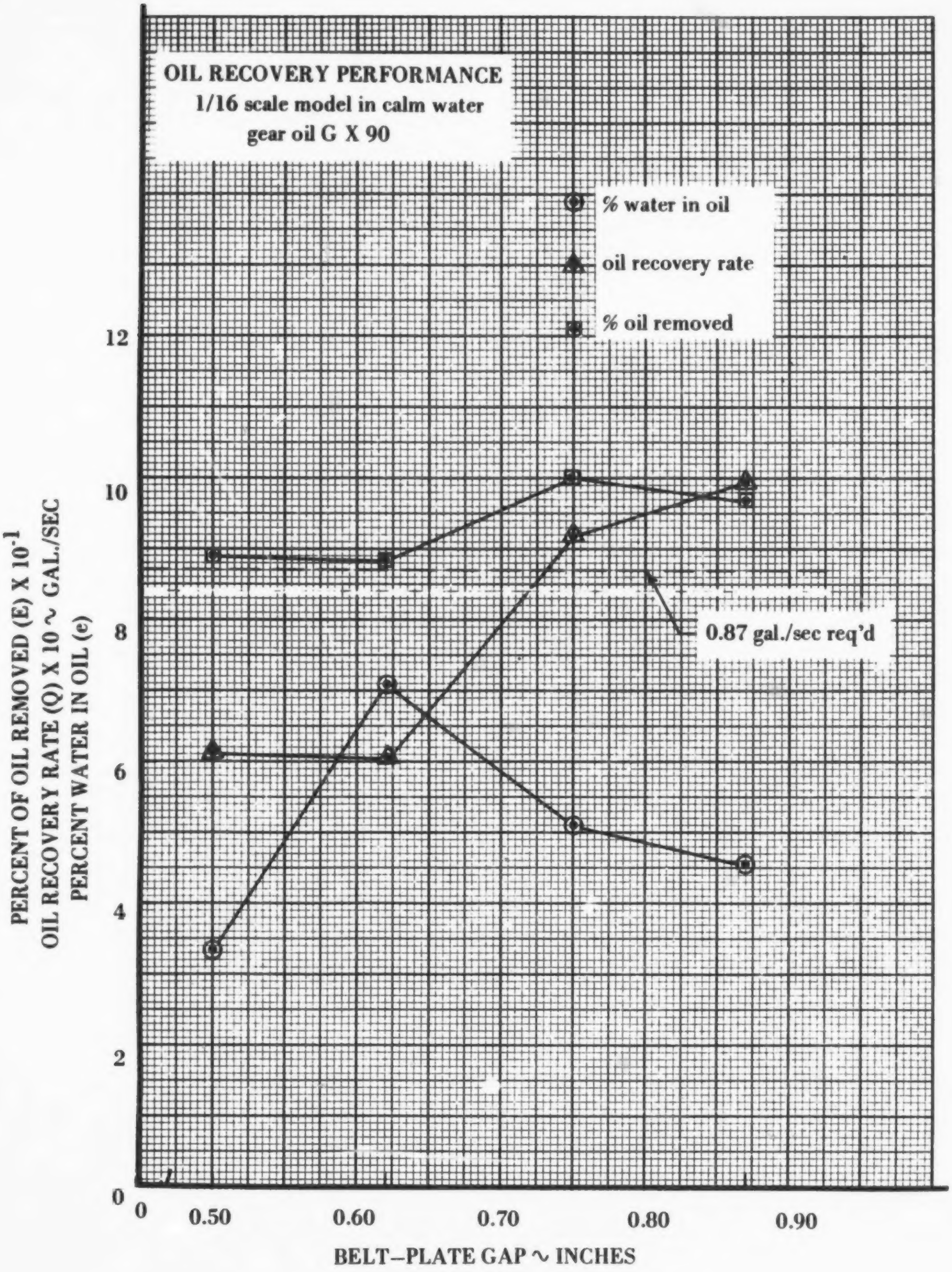


FIGURE 28 – OIL RECOVERY PERFORMANCE

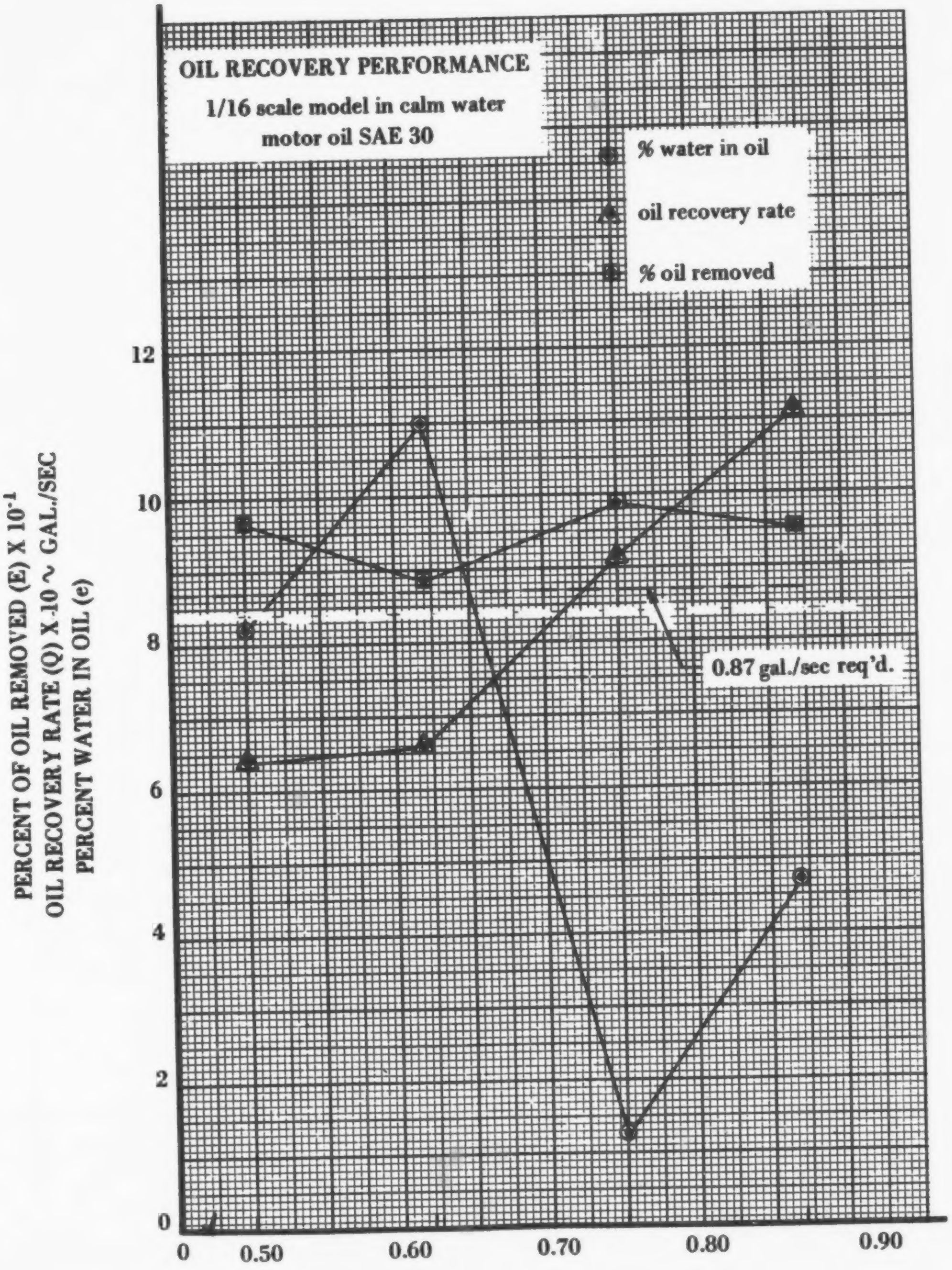


FIGURE 29 – OIL RECOVERY PERFORMANCE

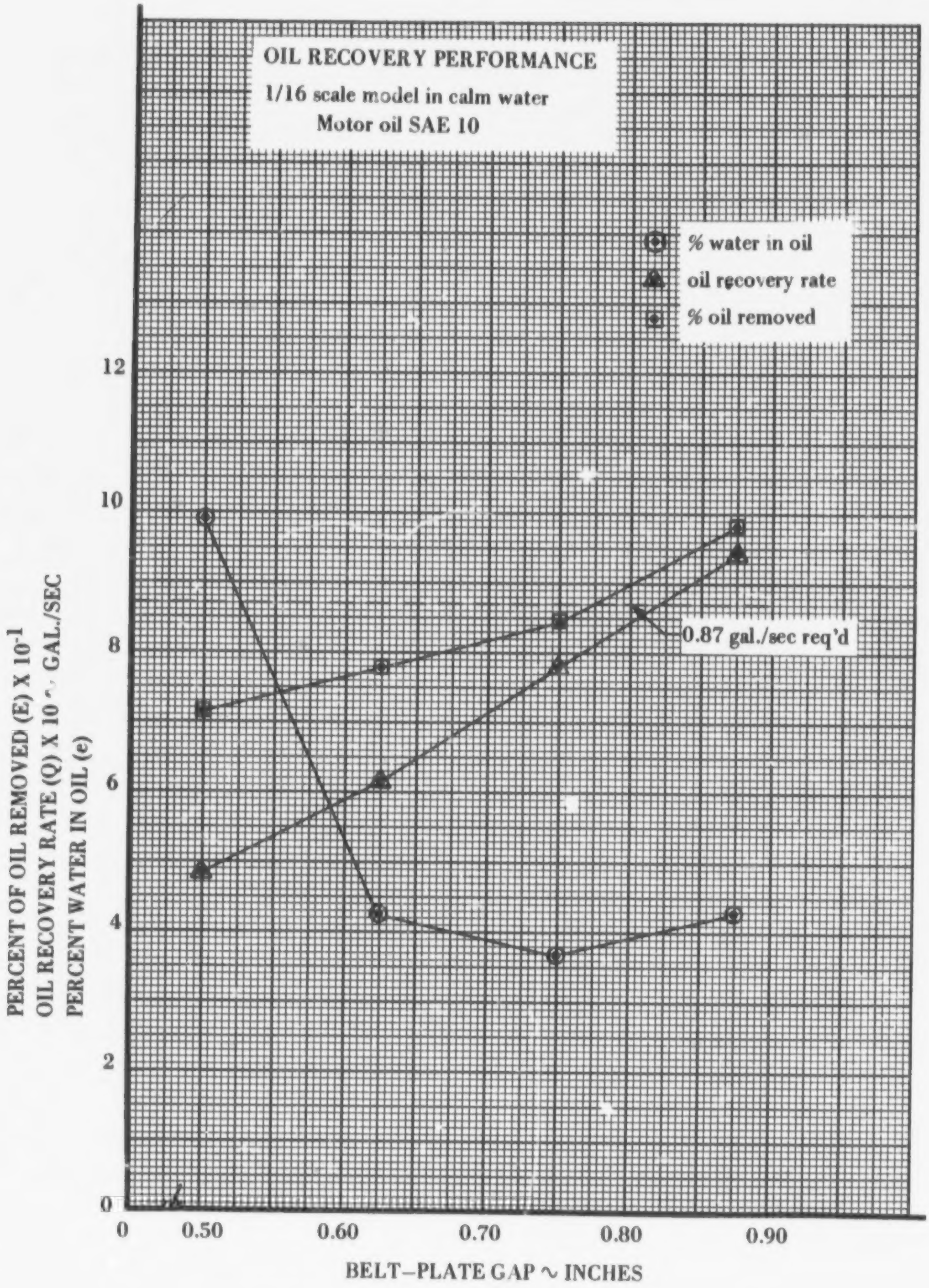


FIGURE 30 – OIL RECOVERY PERFORMANCE

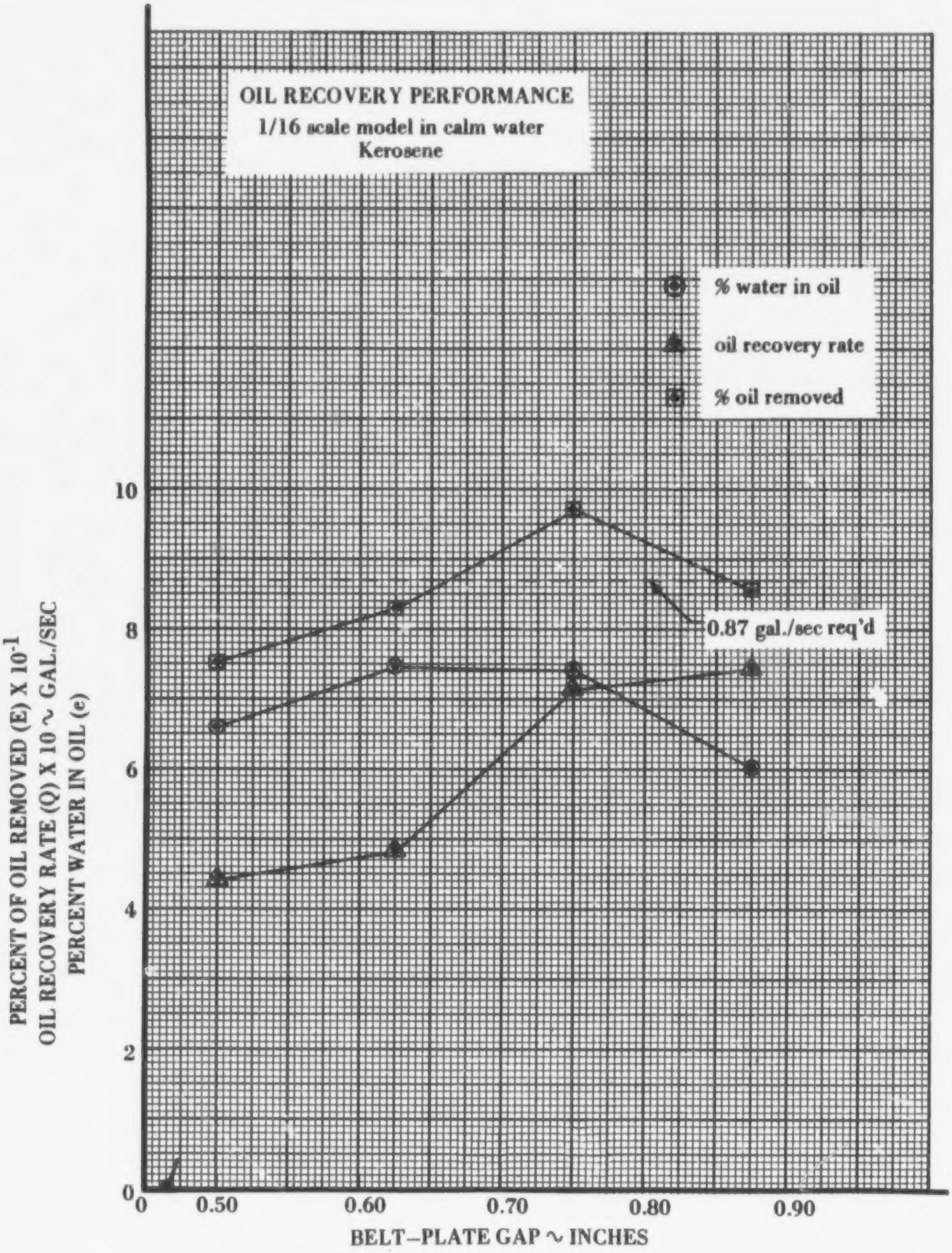
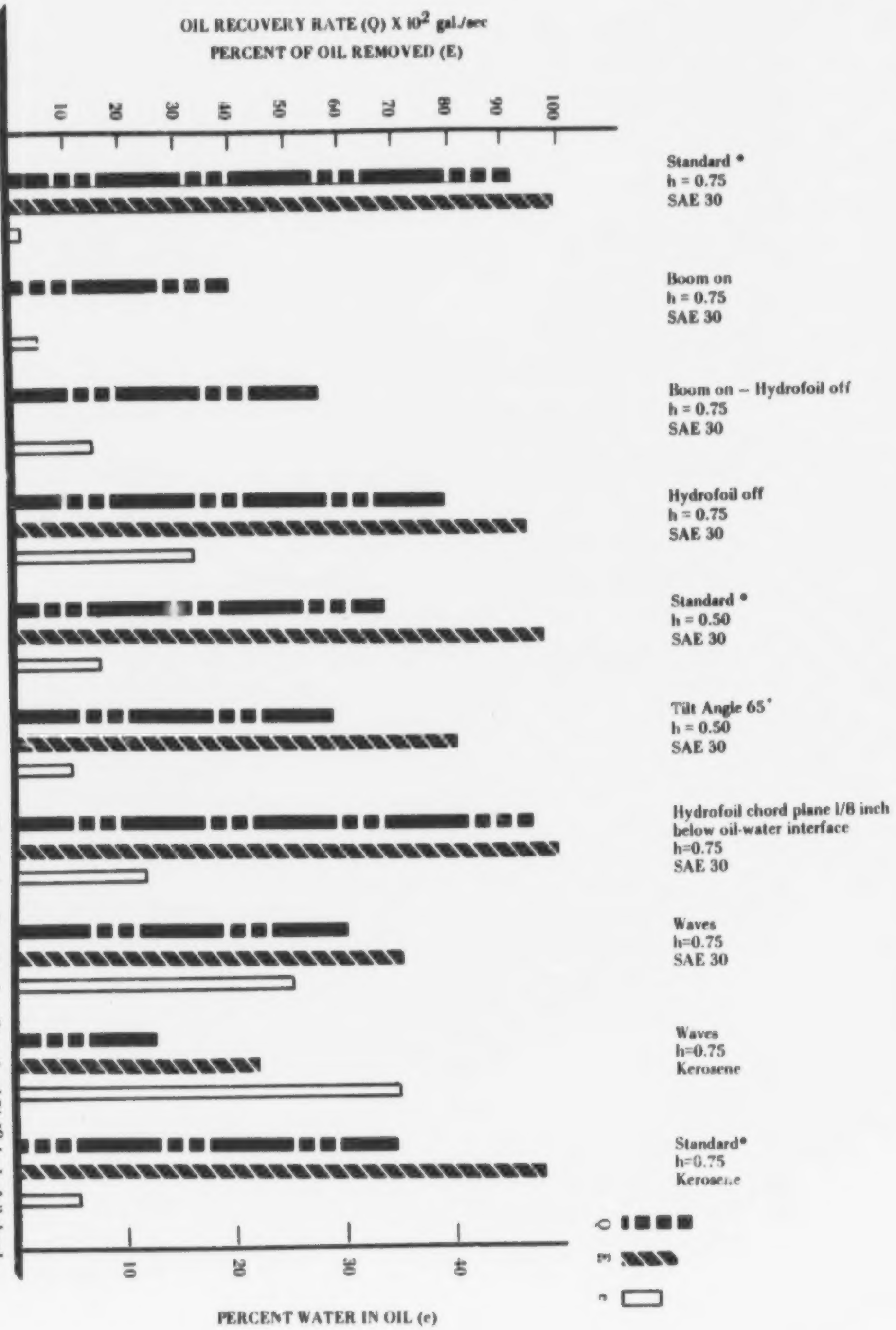


FIGURE 31 – OIL RECOVERY PERFORMANCE



*Standard configuration has tilt angle of 74.2°, hydrofoil chord late.

FIGURE 32 - OIL RECOVERY PERFORMANCE FOR VARIOUS TEST CONFIGURATIONS AND IN WAVES

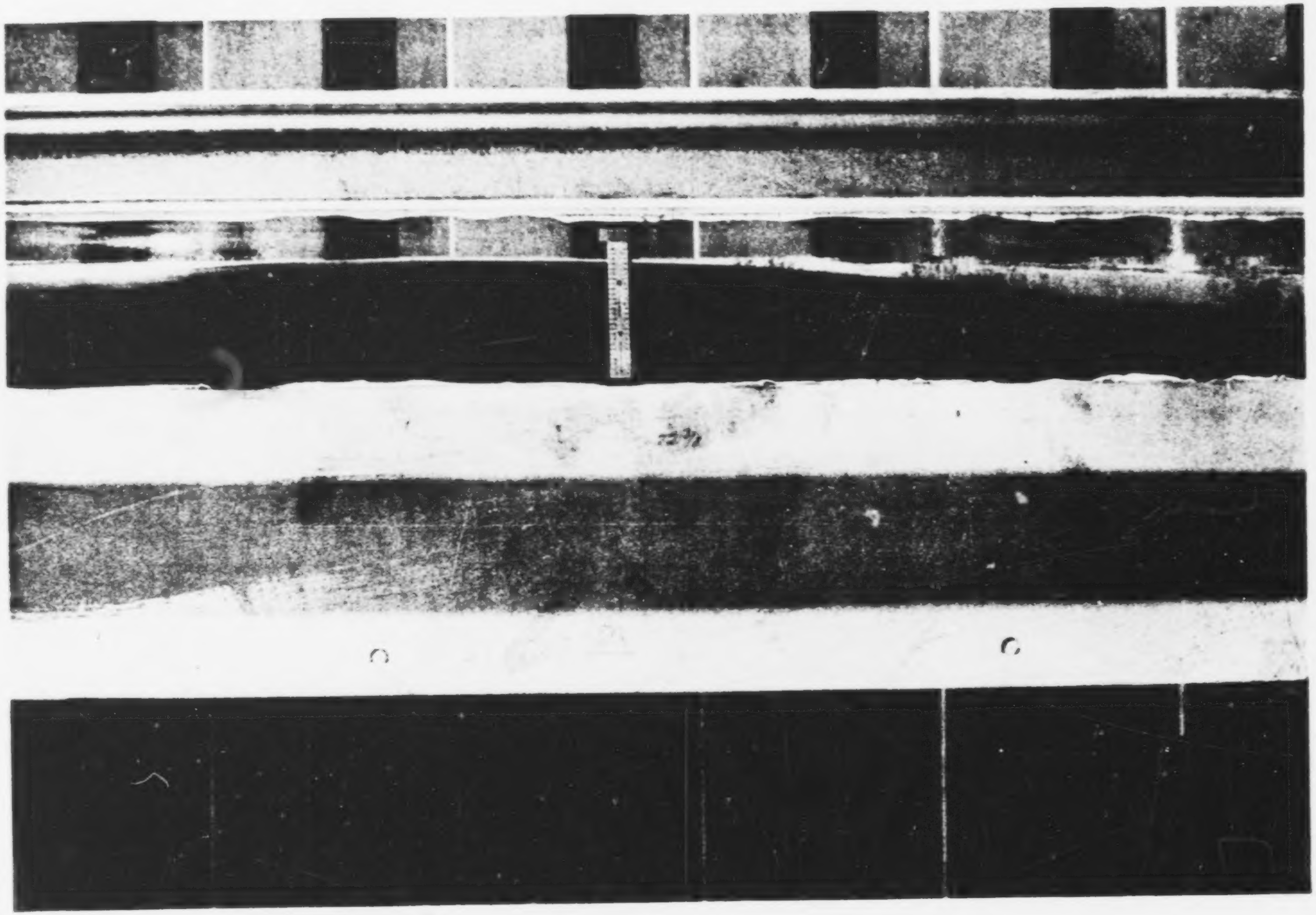


FIGURE 33 – WAVE IN TEST CHANNEL

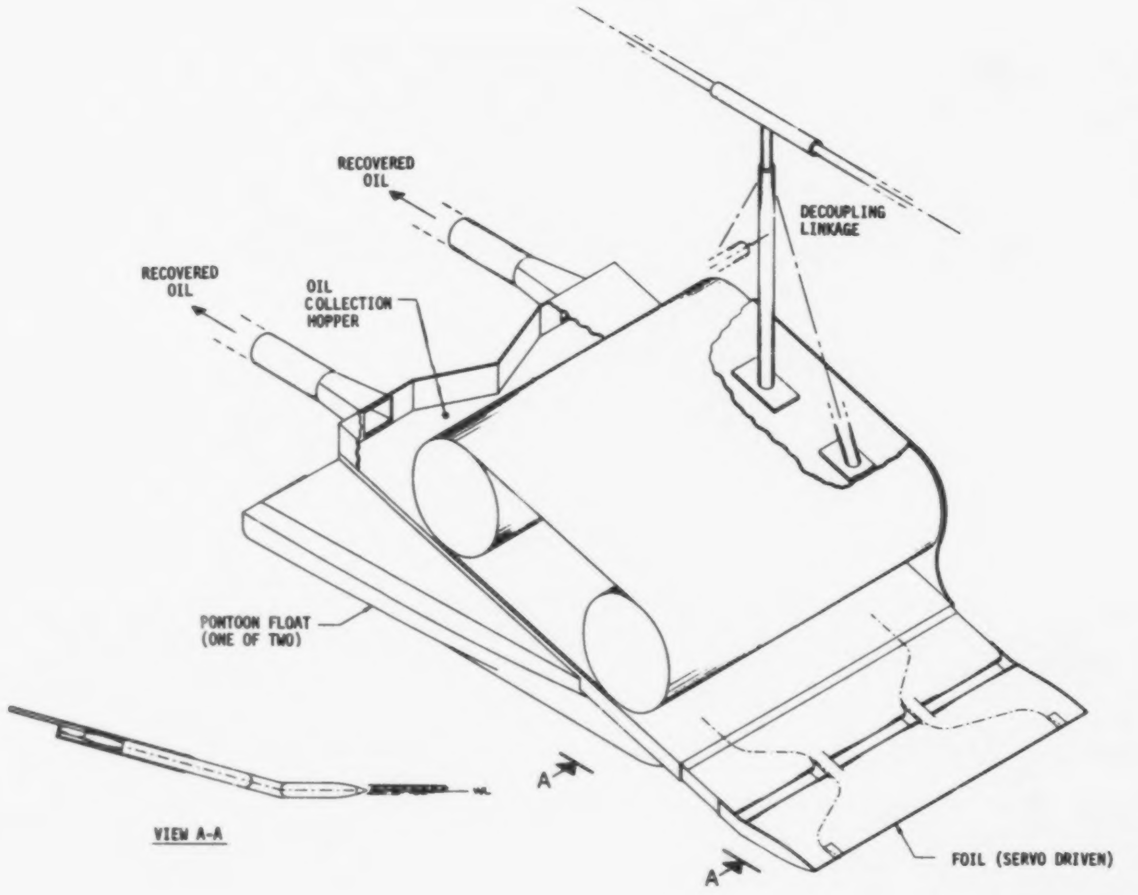

RECOVERED OIL
RECOVERED OIL
OIL COLLECTION HOPPER
DECOUPLING LINKAGE
PONTOON FLOAT (ONE OF TWO)
A
A
WL
VIEW A-A
FOIL (SERVO DRIVEN)

FIGURE 34 – OPU PROTOTYPE CONFIGURATION

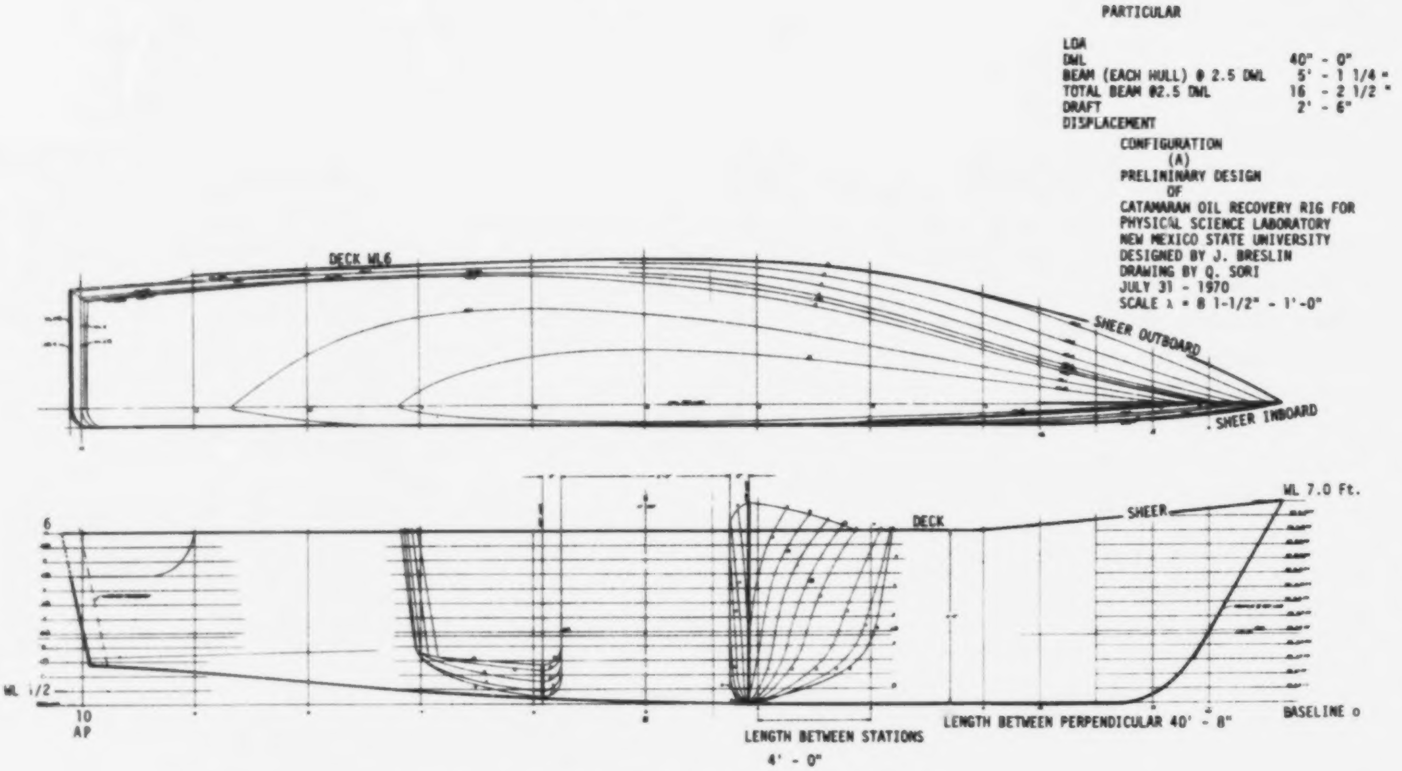
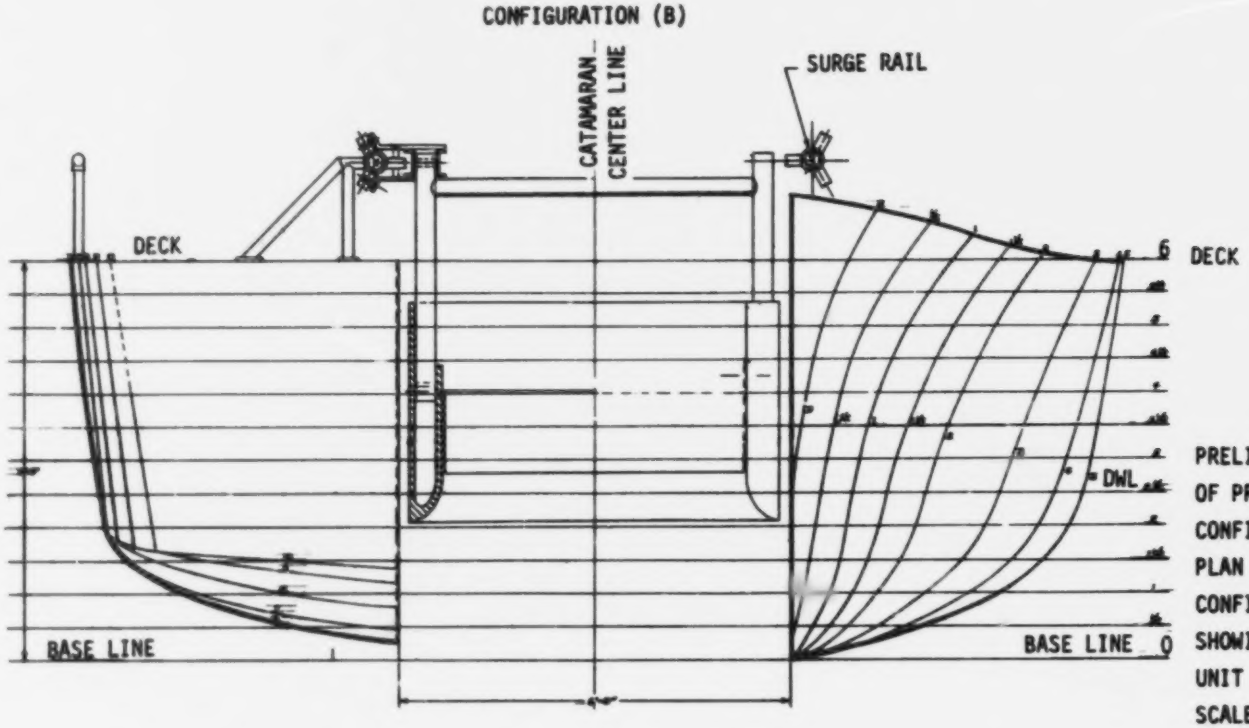

PARTICULAR
LOA
DWL 40" - 0"
BEAM (EACH HULL) @ 2.5 DWL 5' - 1 1/4 "
TOTAL BEAM @2.5 DWL 16 - 2 1/2 "
DRAFT 2' - 6"
DISPLACEMENT
CONFIGURATION
(A)
PRELIMINARY DESIGN
OF
CATAMARAN OIL RECOVERY RIG FOR
PHYSICAL SCIENCE LABORATORY
NEW MEXICO STATE UNIVERSITY
DESIGNED BY J. BRESLIN
DRAWING BY Q. SORI
JULY 31 - 1970
SCALE λ = 8 1-1/2" - 1'-0"
DECK WL6
SHEER OUTBOARD
SHEER INBOARD
WL 7.0 Ft.
SHEER
DECK
6
WL 1/2
10
AP
BASELINE 0
LENGTH BETWEEN STATIONS
4' - 0"
LENGTH BETWEEN PERPENDICULAR 40' - 8"

FIGURE 35 – HULL LINES – CONFIGURATION A


CONFIGURATION (B)
CATAMARAN CENTER LINE
SURGE RAIL
DECK
DECK
6
DWL
BASE LINE
BASE LINE
0

PRELIMINARY DRAWING
OF PROPOSED CATAMARAN
CONFIGURATION (B) BODY
PLAN (SAME PROFILE AS
CONFIGURATION A)
SHOWING OIL PICKUP
UNIT
SCALE λ = 8

FIGURE 36 – HULL BODY PLAN – CONFIGURATION B

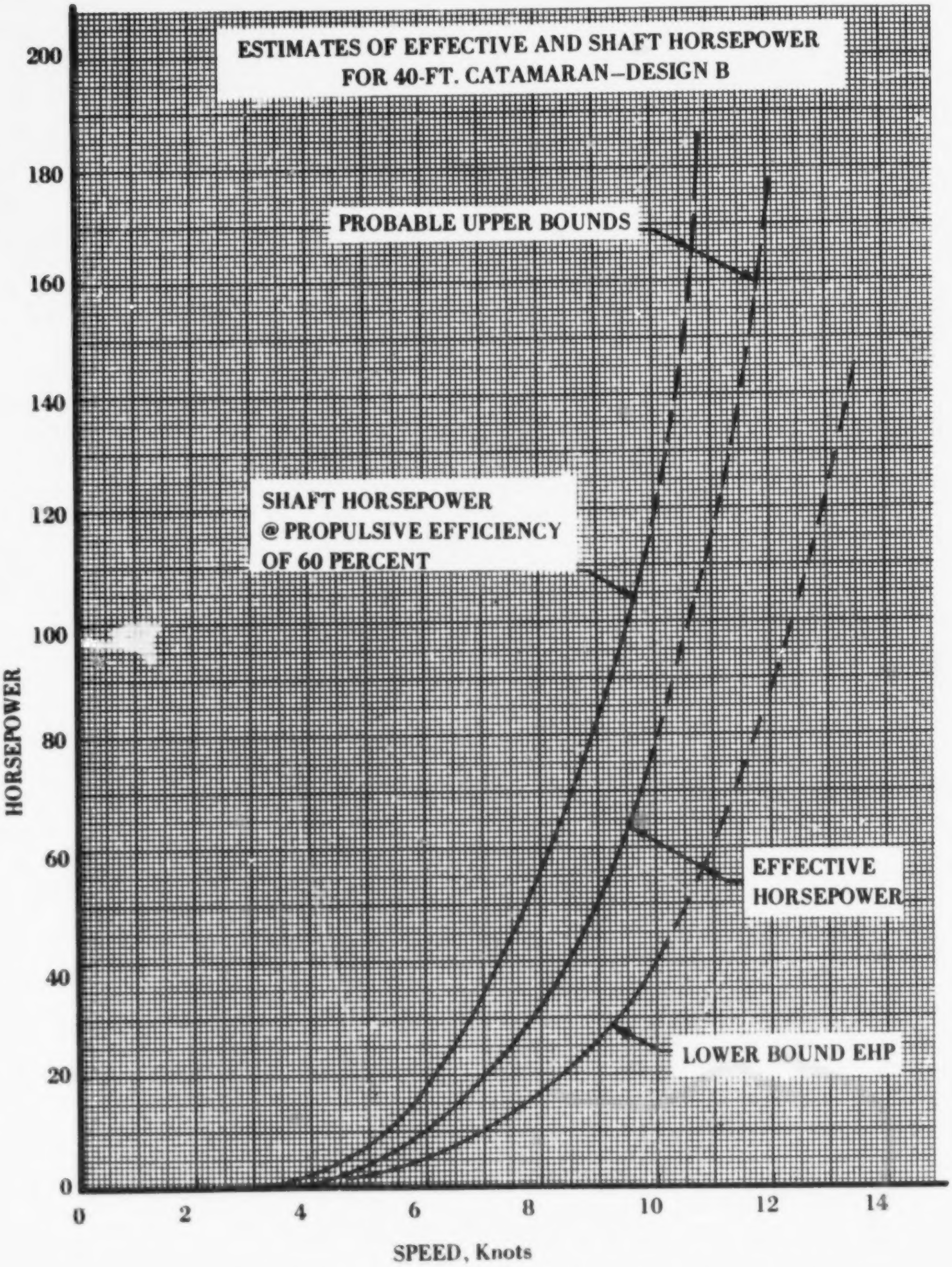


FIGURE 37 – HORSEPOWER REQUIRED–CATARMARAN

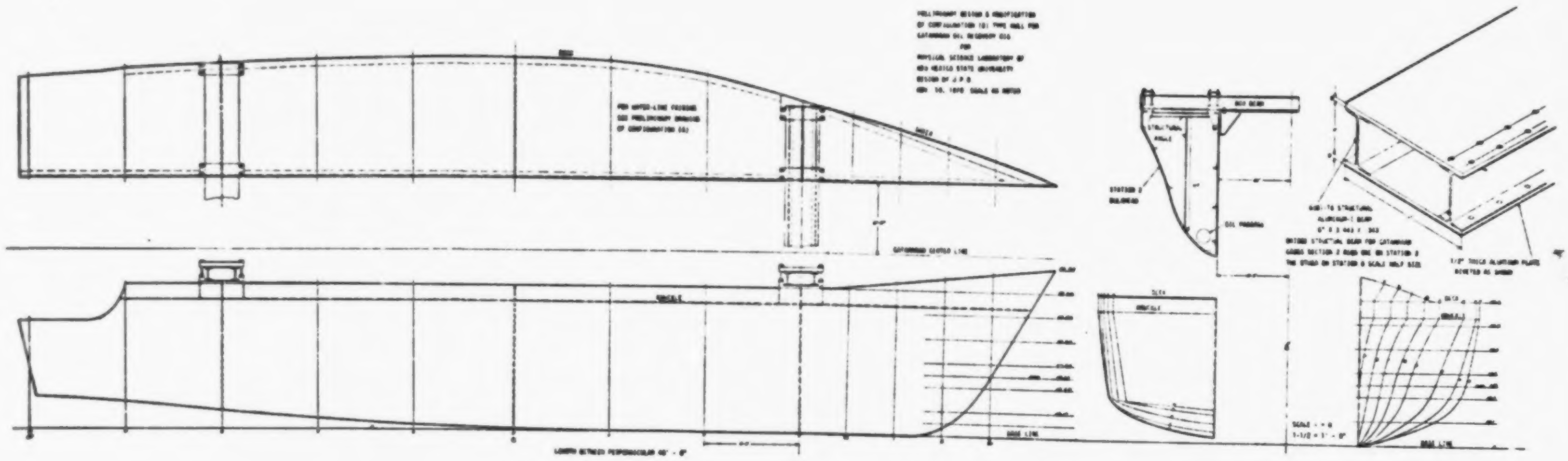


FIGURE 38 – CATAMARAN OIL RECOVERY VESSEL

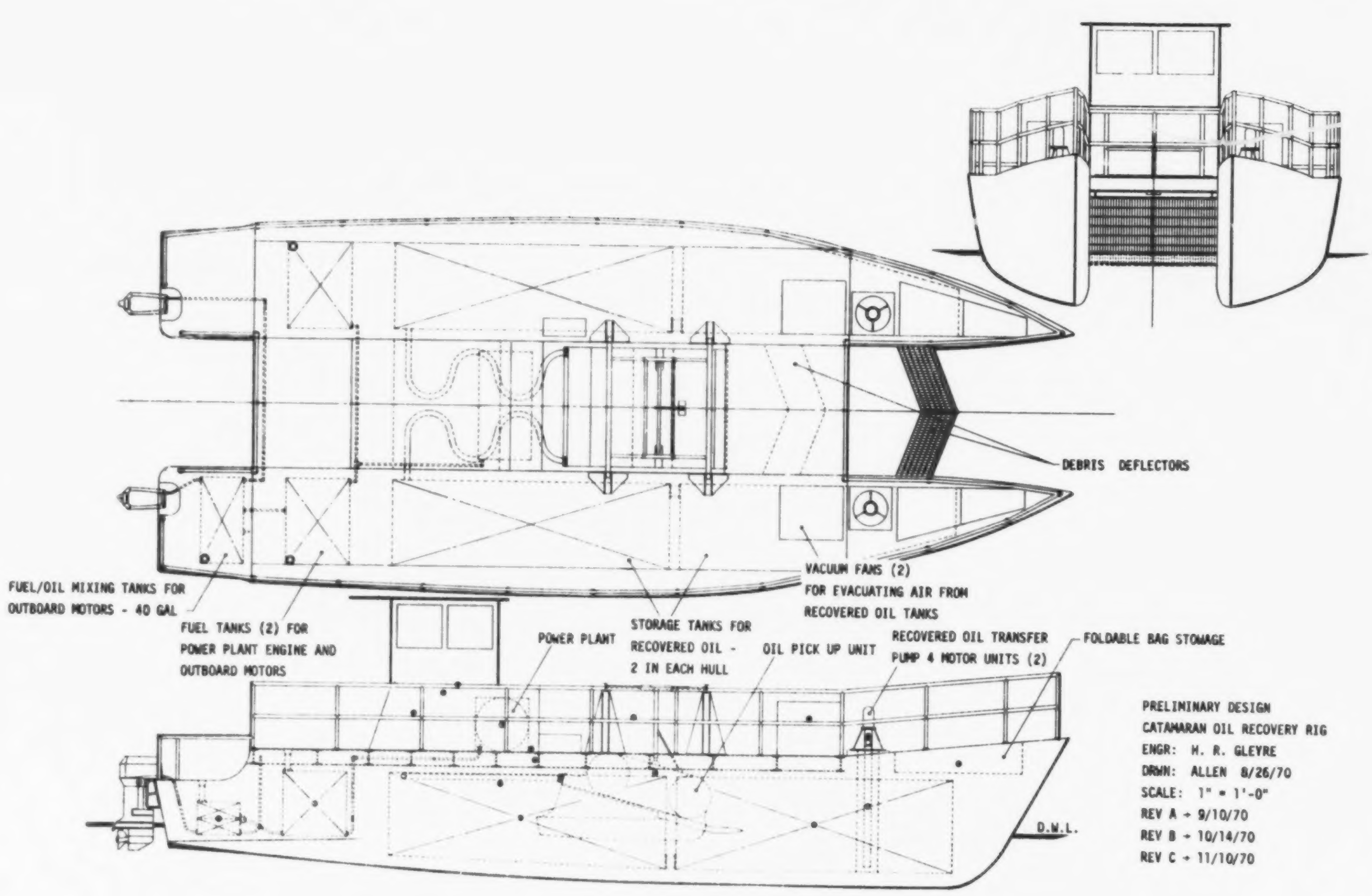

DEBRIS DEFLECTORS
VACUUM FANS (2)
FOR EVACUATING AIR FROM
RECOVERED OIL TANKS
FUEL/OIL MIXING TANKS FOR
OUTBOARD MOTORS - 40 GAL
FUEL TANKS (2) FOR
POWER PLANT ENGINE AND
OUTBOARD MOTORS
POWER PLANT
STORAGE TANKS FOR
RECOVERED OIL -
2 IN EACH HULL
OIL PICK UP UNIT
RECOVERED OIL TRANSFER
PUMP 4 MOTOR UNITS (2)
FOLDABLE BAG STOWAGE
D.W.L.
PRELIMINARY DESIGN
CATAMARAN OIL RECOVERY RIG
ENGR: H. R. GLEYRE
DRWN: ALLEN 8/26/70
SCALE: 1" = 1'-0"
REV A + 9/10/70
REV B + 10/14/70
REV C + 11/10/70

FIGURE 39 – CATAMARAN BRIDGE AND HULL STRUCTURE

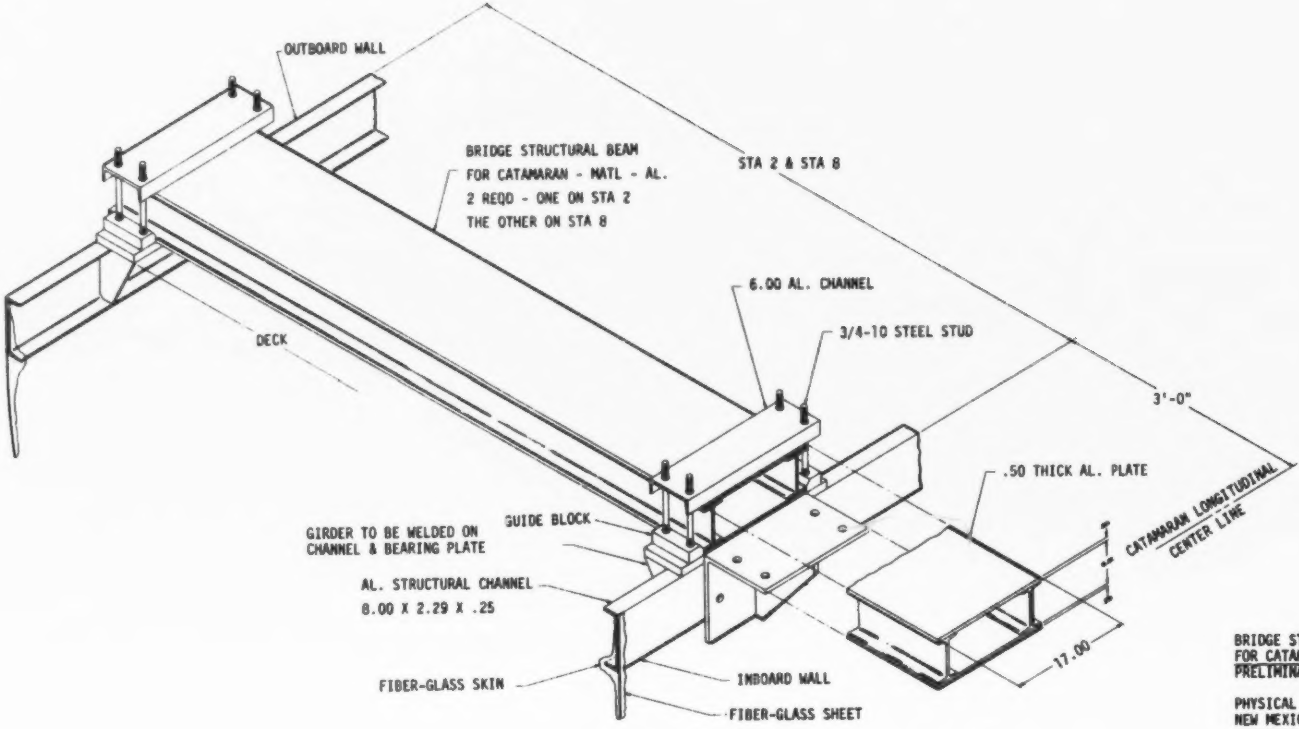

OUTBOARD WALL
BRIDGE STRUCTURAL BEAM
FOR CATAMARAN - MATL - AL.
2 REQD - ONE ON STA 2
THE OTHER ON STA 8
STA 2 & STA 8
6.00 AL. CHANNEL
3/4-10 STEEL STUD
DECK
3'-0"
.50 THICK AL. PLATE
CATAMARAN LONGITUDINAL
CENTER LINE
GUIDE BLOCK
GIRDER TO BE WELDED ON
CHANNEL & BEARING PLATE
AL. STRUCTURAL CHANNEL
8.00 X 2.29 X .25
17.00
FIBER-GLASS SKIN
INBOARD WALL
FIBER-GLASS SHEET

FIGURE 40 – CATAMARAN BRIDGE STRUCTURAL BEAM

BRIDGE STRUCTURAL BEAM
FOR CATAMARAN ASSEMBLY
PRELIMINARY DESIGN

PHYSICAL SCIENCE LABORATORY
NEW MEXICO STATE UNIVERSITY
DESIGN BY: J.P. BRESLIN
DATE: 10 NOV 1970
SCALE: λ-4 3" = 1'-0"

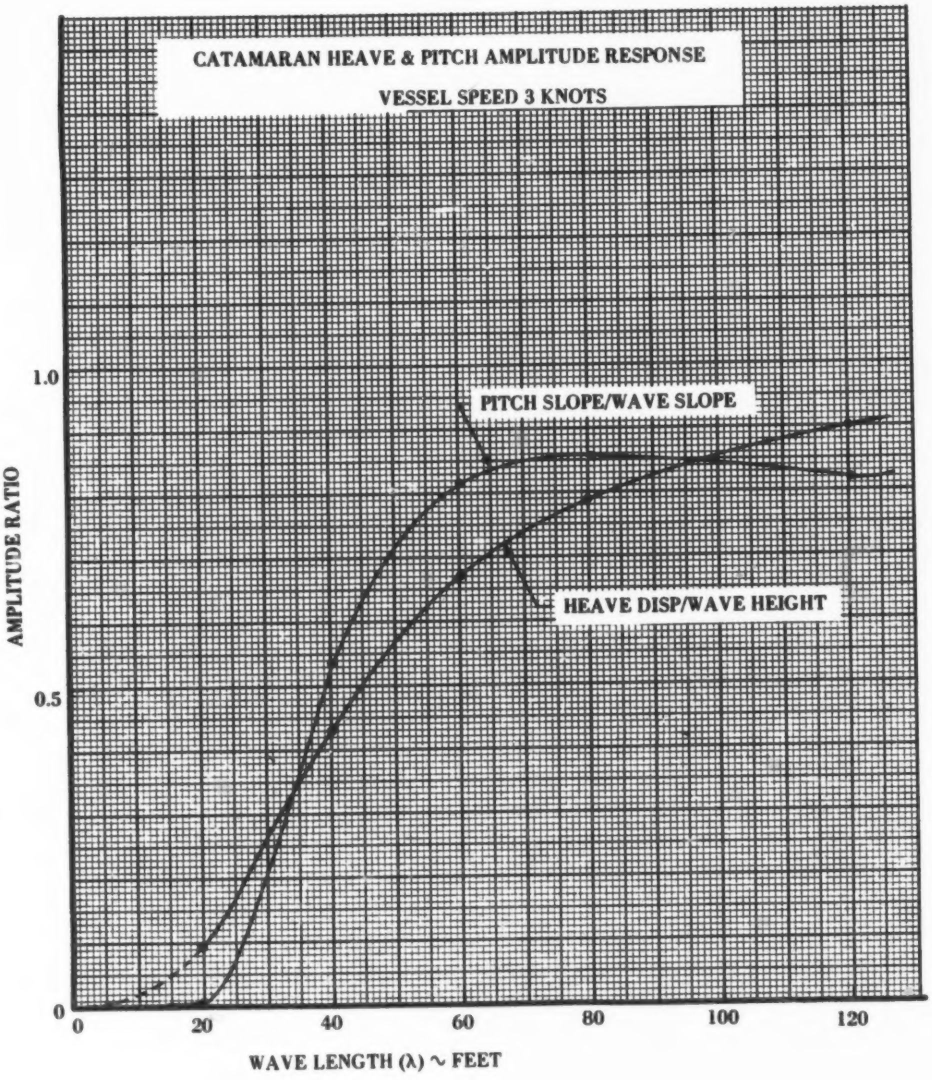


FIGURE 41 – CATAMARAN HEAVE & PITCH AMPLITUDE RESPONSE

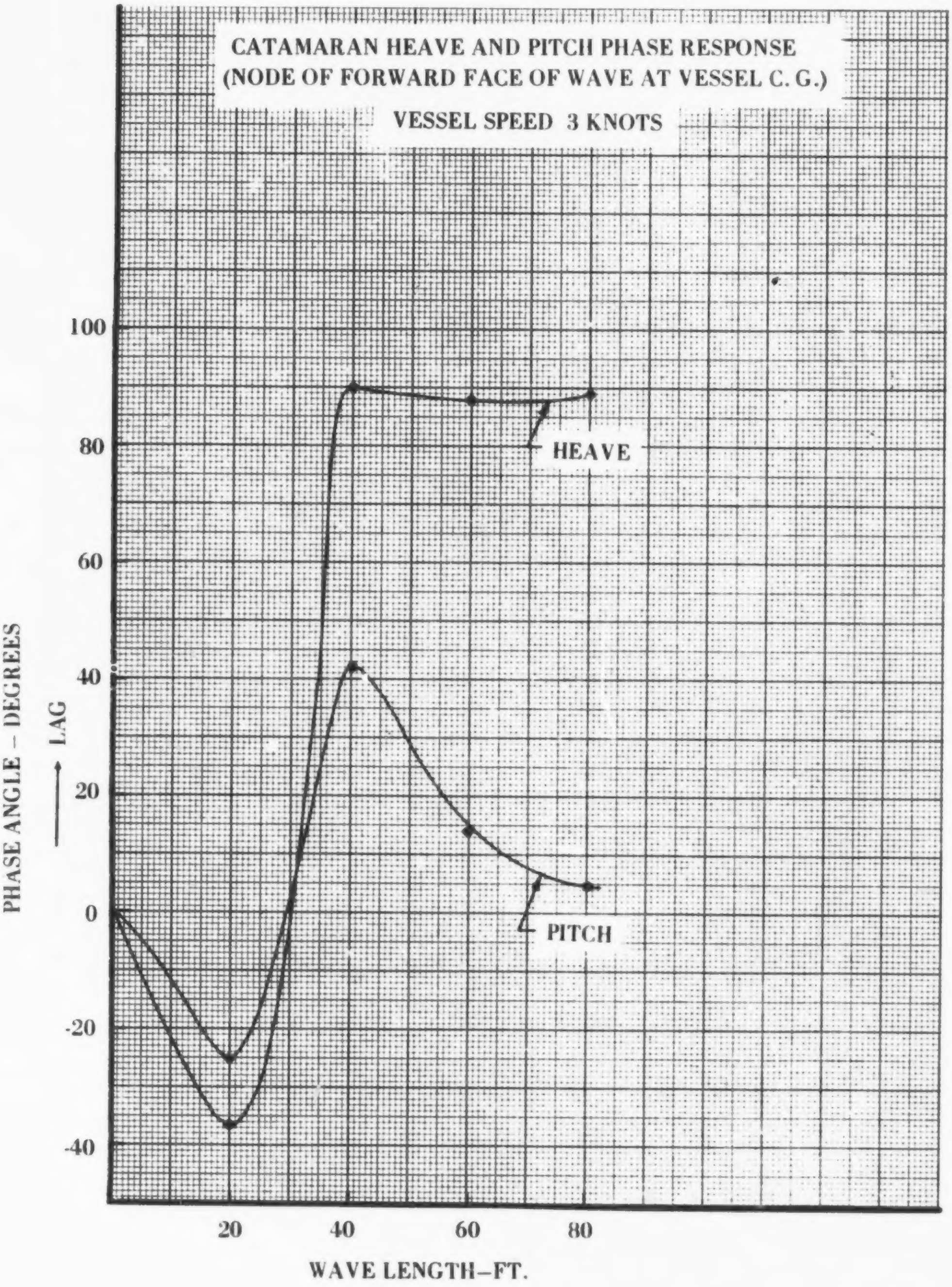


FIGURE 42 – CATAMARAN HEAVE & PITCH PHASE RESPONSE

APPENDIX B

ESTIMATION OF THE WAVE LENGTHS FOR SUITABLE OPERATION OF THE OIL PICKUP UNIT AND RECOMMENDATIONS FOR AN EXTENSION OF THE DEVELOPMENT PROGRAM

by

J. P. Breslin
Consultant

Prepared for
Physical Science Laboratory
New Mexico State University

10 November 1970

INTRODUCTION

It is necessary to ascertain the range of encounter frequencies over which the dynamic responses of the OPU will be larger than that of the wave. The actual motions are difficult, if not impossible, to calculate with acceptable accuracy because of the fact that the draft of the flotation device is generally not sufficiently large with respect to the wave amplitudes to permit confident application of existing methods. Furthermore, the geometry of the scoop inlet falls beyond available experience for the estimation of the various hydrodynamic coefficients required by the linear analysis of floating bodies in waves. Within the framework of linear analysis, estimates of the wave lengths for which the relative motions will be likely to be unacceptable can be made.

EQUATIONS OF MOTION

It is assumed that the OPU is connected by freely pivoting or translating links to a carriage which is free to surge fore and aft on virtually frictionless guides attached to the catamaran. The linkage and carriage will provide inertia forces and moments to the OPU. At the outset, these constraints will be considered to be small. It is also assumed that the OPU is towed by a cable which provides a spring-type restoring force to keep the mean position near to the mid-length of the catamaran.

If the unit is beset with regular waves of frequency ω (radians/sec) while moving forward with speed U, then the forced response will be at the wave encounter frequency Ω which, for head seas, is given by

$$\Omega = 2\pi \frac{(c+U)}{\lambda} \qquad (1)$$

where c is the wave celerity which depends upon wave length

λ is the wave length

In terms of wave length, this is

$$\Omega = \frac{2\pi}{\lambda} \left(\sqrt{\frac{g\lambda}{2\pi}} + U\right) \qquad (2)$$

Values of encounter frequency Ω for selected forward speed are graphed in Figure 43 as a function of wave length λ.

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When the excitation is at frequency Ω, the motion response under assumption of linearity of the system will be at this single frequency. If x and z are the instantaneous coordinates of the excursions of the center of mass of the OPU with respect to a frame of reference moving at constant speed, and θ the angle of pitch from the horizontal, then it is convenient to split off the time dependence by writing

$$x = \bar{x}e^{i\Omega t}$$

$$z = \bar{z}e^{i\Omega t} \tag{3}$$

$$\theta = \bar{\theta}e^{i\Omega t}$$

where $\bar{x}$, $\bar{z}$ and $\bar{\theta}$ are *complex* amplitudes in surge, heave and pitch. The real parts of these expressions are ultimately retained.

The equations of motion are, in general, given in the form:

$$\begin{vmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{vmatrix} \begin{Bmatrix} \bar{x} \\ \bar{z} \\ \bar{\theta} \end{Bmatrix} = \begin{Bmatrix} \bar{F}_x \\ \bar{F}_z \\ \bar{M} \end{Bmatrix} \tag{4}$$

For example, the equation for heave is

$$A_{21}\bar{x} + A_{22}\bar{z} + A_{23}\bar{\theta} = \bar{F}_z \tag{5}$$

The quantities A_{ij} are complex force or moments per unit amplitude of response. For example, the term $A_{21}\bar{x}$ is the heave force due to surge and, therefore, represents a cross-coupling of surge into heave. A_{12} is the surge force due to heave. The quantities on the right side of (4) are the wave-exciting forces and moments. Each of the quantities A_{ij} are of the form

$$A_{ij} = (-\omega^2 a_{ij} + c_{ij} + i\omega b_{ij}) \tag{6}$$

To be specific

$$A_{11} = (-\omega^2 a_{11} + c_{11} + i\omega b_{11}) \tag{7}$$

Here the first term $-\omega^2 a_{11}$ is the force associated with surge acceleration of the body in calm water, a_{11} being the force per unit acceleration, being the sum of the mass of the body plus the entrained fluid mass in surge. The quantity c_{11} is the restoring or spring force in surge per unit amplitude of surge. This is usually zero for ships and may be zero for the OPU if a constant tension winch-cable system is employed to balance the mean drag force acting on the unit at constant forward speed. The term b_{11} is the damping force in surge per unit amplitude due to motion induced by surge.

The wave-exciting forces are of the form

$$\bar{F}_x = (-\omega^2 A_1 + C_1 + i\omega B_1)\bar{\eta} \tag{8}$$

where A_1 is the force per unit wave acceleration $-\omega^2\bar{\eta}$, $\bar{\eta}$ being the complex wave amplitude

C_1 is the hydrostatic force per unit $|\bar{\eta}|$ in surge

B_1 is the surge force arising from wave velocity

It may be seen from these expressions that there are, in general, 27 body coefficients and 9 wave-generated coefficients which must be known in order to solve the equation system (4). Fortunately, not all are distinct and many of the cross-coupling coefficients are either zero or negligible because of symmetries or near symmetries in the hull form.

The body coefficients a_{ij} and b_{ij} are generally obtained by oscillating a model in calm water to obtain that part of a_{ij} which is due to the added mass of the fluid and the damping force coefficient b_{ij}. The restoring forces c_{ij} are calculated from hydrostatic principles. The added mass and damping can be calculated for certain simplified forms generally applying two-dimensional theory. More general methods for arbitrary forms also exist which employ computer programs.

The wave-exciting force coefficients A_j, B_j are frequently obtained from tests in which a model is held fixed in waves of discrete frequencies. Calculational procedures are also available.

It must be appreciated that, because of its unusual form, the OPU does not belong to a class of shapes for which a body of knowledge exists. In the absence of specific measurements of the body coefficients (a_{ij}, b_{ij}) and the wave-exciting coefficients (A_j, B_j), it is indeed impossible to make specific motion predictions over the entire frequency or wave length regime of interest. This is particularly true for the OPU where the error in the prediction of the motion of the leading edge must be less than a fraction of the oil film thickness at that location.

However, the equations do provide an opportunity to assess the natural frequencies in the separate modes which ought to be strived for in order to assure that the OPU will respond closely to the wave over a large range of encounter frequencies.

For example, consider heave under the assumption that the cross-couplings from surge and pitch are negligible. Then, from Equations (4) and (6), we have

$$(-\omega^2 a_{22} + c_{22} + i\omega b_{22})\bar{z} = -\omega^2 A_2 + C_2 + i\omega B_2 \tag{9}$$

The undamped, uncoupled natural frequency in heave is then

$$\omega_2 = \sqrt{\frac{c_{22}}{a_{22}}} \tag{10}$$

In order to proceed with an estimate of ω_2, it is necessary to specify the proportions of the flotation configuration.

Suppose that two slender catamaran hulls support the OPU. Let the weight w of the OPU be assumed to be 320 pounds. If the waterplane area is A, then the natural frequency of each hull is

$$\omega_2 = \sqrt{\frac{\gamma A}{\frac{w}{g} + \frac{\gamma V_a}{g}}} \tag{11}$$

where V_a is the entrained or added volume of the fluid induced by the heaving motion

γ is the weight density of sea water

g the acceleration due to gravity

Since the body is floating $w = \gamma V$; a close approximation for the volume V_a is the displaced volume V. Hence

$$\omega_2 = \sqrt{\frac{g}{2} \cdot \frac{A}{V}} \tag{12}$$

The waterplane area, when multiplied by the draft and the vertical prismatic coefficient, is equal to the volume V, i.e.

$$A = \frac{V}{C_v \cdot h} \tag{13}$$

Hence

$$\omega_2 = \frac{4}{\sqrt{C_v \cdot h}} \tag{14}$$

Selecting $C_v = 0.72$ and $h = 0.5$ ft gives a heave natural frequency:

$$\omega_2 = \frac{4}{\sqrt{0.36}} = 6.67 \text{ rad/sec.} \tag{15}$$

The waterplane area $A = 6.95 \text{ ft}^2$; taking a length of 8 feet and a waterplane coefficient of 0.7, gives the maximum beam $b = 1.25$ ft.

Entering Figure 43 with this natural frequency indicates that the OPU so supported will experience resonance at wave lengths of 12, 18 and 26 feet at advance speeds of 3, 6 and 10 knots respectively. As the exciting forces will achieve their maximum value for wave lengths of the order of three times the waterplane length, the maximum response will occur at wave lengths larger than 12 and 18 feet for 3 and 6 knots. Considering that response dies off appreciably for incident frequencies less than half of the natural frequency, it may be concluded that, for wave lengths less than 40, 58 and 77 feet, the response due to heave alone may be unacceptably large.

For such long waves (compared to the waterline length) an estimate of the heave response is (for small wave amplitudes)

$$\frac{\bar{z}}{\bar{\eta}} = \frac{C_2 - \Omega^2 A_{22}}{c_{22} - \Omega^2 a_{22}} \tag{16}$$

upon ignoring damping and the wave forcing term proportional to wave velocity $\dot{\eta}$. For this condition $C_2 = c_{22} = \gamma A$, $A_{22} = w/g$ and $a_{22} = 2w/g$. Inserting these values in (16) yields

$$\frac{\bar{z}}{\bar{\eta}} = \frac{1 - \Omega^2 \frac{w}{g\gamma A}}{1 - 2\Omega^2 \frac{w}{g\gamma A}} \tag{17}$$

Using the values $w = 160$ lbs.; $A = 6.95$; $g = 32$ ft/sec^2; $\gamma = 64$ lbs/ft^3 gives

$$\frac{\bar{z}}{\eta} = \frac{1 - 0.0113\Omega^2}{1 - 0.0226\Omega^2}$$

For an encounter frequency $\Omega = 3$ (corresponding to meeting waves of 40, 58 and 77 ft. at speeds of 3, 6 and 10 knots)

$$\frac{\bar{z}}{\eta} = \frac{1 - 0.10}{1 - 0.20} = 1.12 \tag{18}$$

In view of the fact that response in irregular waves is generally smaller than in regular waves, the excursions due to heave alone will be generally acceptable for waves in excess of 40, 58 and 77 ft. in length at 3, 6 and 10 knots. The mitigating effects of the oil on wave amplitude will also help.

The response in pitch and the relative phase of heave and pitch depends upon a knowledge of the mass moment of inertia of the OPU which is not available at this time.

To achieve close following of the waves, it is essential to reduce the inertia of the OPU. If the "belt-pump" concept is retained, it may be necessary to transmit the drive by means of a flexible shaft to remove the weight of the driving motor or to use an hydraulic pump with flexible hoses to the hydraulic motor located on the catamaran. Otherwise, if the number of short waves is great (as the writer expects in coastal waters) it will be necessary to activate the inlet scoop lip with a pitching control servoed to the oil layer thickness. To design this system effectively, it would appear necessary to characterize the coupled motions of the catamaran – OPU system by means of a carefully scaled model test since the tolerance required for the inlet scoop submergence appears so severe as to preclude dependence on existing methods of calculations, even if all the body and exciting force (and moment) coefficients were known from oscillator and restrained model measurements in waves.

RECOMMENDATIONS

It is recommended that a program seeking extension of support be sought which includes development of a configuration

a) of very low inertia

b) exploiting a phenomenon which would accommodate relative motion of the inlet relative to the water surface, i.e., the planing concept which will skim a layer proportional to the square of the trim angle of a planing plate;

c) employing a vacuum system to assist the upward flow of the oil and thereby eliminate the need for weight on the OPU, placing machinery and oil storage directly on and into the catamaran hulls;

d) characterized by means of a model test program to secure the motions of the OPU-catamaran system in a sequence of regular waves.

Adoption of these concepts should result in an OPU which is extremely light and should, at the same time, eliminate the need for booms to funnel the oil. The rate of recovery could be achieved by operating at higher speeds than contemplated with the presently conceived system.

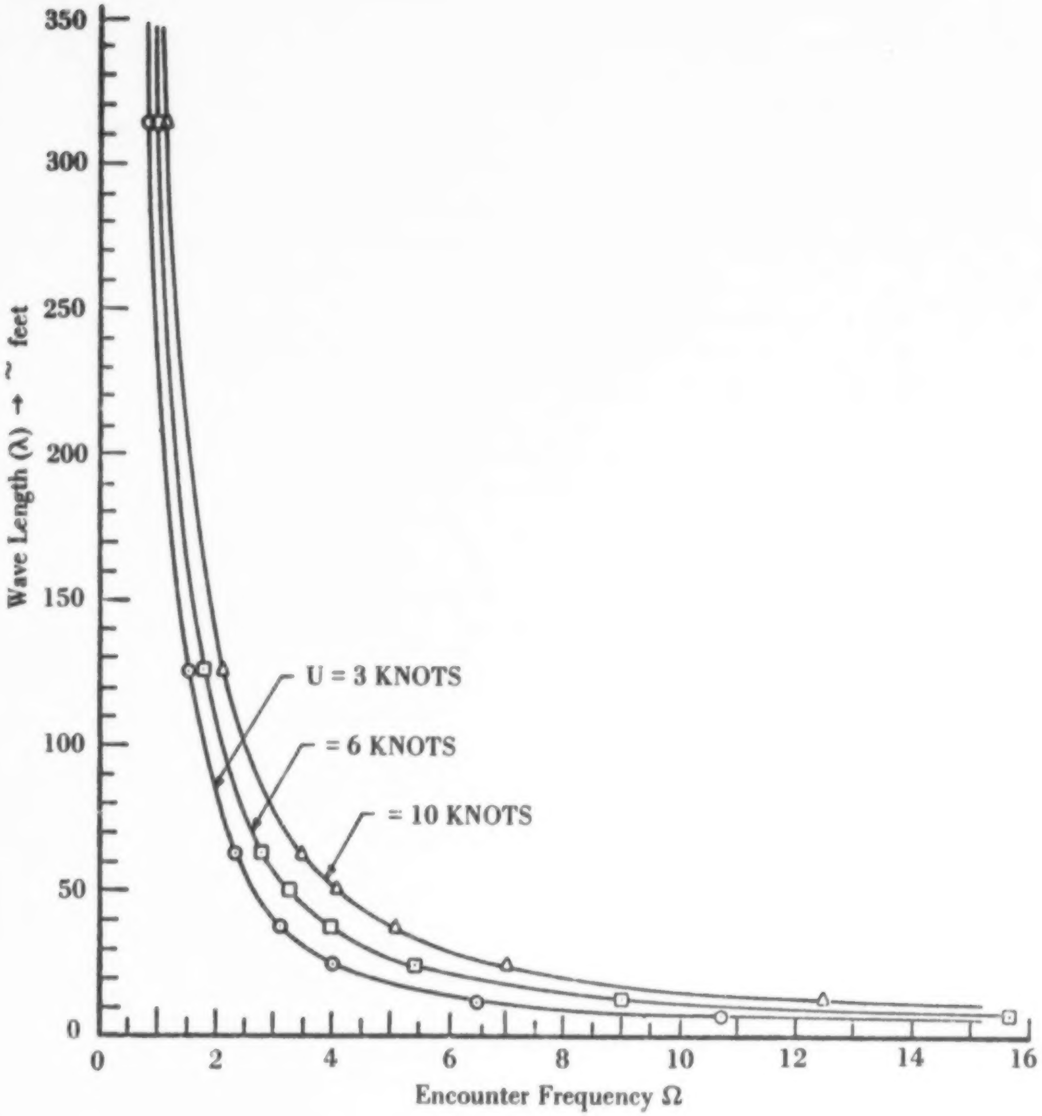

FIGURE 43 – WAVE LENGTHS FOR VARIOUS ENCOUNTER FREQUENCIES AT SELECTED SPEEDS

1 Accession Number

2 Subject Field & Group
05G

SELECTED WATER RESOURCES ABSTRACTS
INPUT TRANSACTION FORM

5 Organization
New Mexico State University
Physical Science Laboratory
Las Cruces, New Mexico

6 Title

FLOATING OIL RECOVERY DEVICE

10 Author(s)

16 Project Designation
15080 FWO

21 Note

22 Citation
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February 1971 43 Figures, 1 Reference.

23 Descriptors (Starred First)

*Floating oil recovery, *oil removal, *water channel, *oil spill, *model, *tests, device, vessel, test channel, oil recovery rate, oil recovery efficiency, oil recovery performance.

25 Identifiers (Starred First)

*Oil pickup unit (OPU), *belt/plate, *rotating belt, *Couette flow, *catamaran.

27 Abstract

Flow bench tests of a model rotating belt-Couette flow oil recovery device were conducted in a calm water environment primarily, although a few tests were conducted in the presence of waves. These tests revealed clearly that the device is capable of harvesting oils over a broad range of viscosities at the rates and purities specified by the EPA, if the inlet can be made to "track" the water surface.

Analyses were conducted to design a catamaran vessel suitable for mounting the Oil Pickup Unit (OPU) and also providing the requisite surface following performance. Vessel response analyses showed that the required surface following behavior cannot be provided by the catamaran itself, but can be achieved by floating the OPU and decoupling this assembly from the vessel in heave and surge. A servo control for the foil device used at the OPU inlet will further enhance the surface tracking behavior.

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